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THESIS

A MARKET PRICING METHOD

FOR SPECTRUM ALLOCATION

by

Joseph Philip Woodford

March 1980

Thesis Advisor: Dan C. Boger

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A Market Pricing Method
for Spectrum Allocation

by

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ABSTRACT

This thesis is a study of spectrum allocation by market incentives as an alternative to the conventional block allocation scheme administered under government regulation. A description of electromagnetic radiation and a brief history of allocation introduce this study. The principal elements of concern are allocative efficiency under regulation, technology and spectrum substitutability in a user's production decision, and the problems inherent in a spectrum market, specifically, property right definition, negative externalities of spectrum use, and transaction costs. The potential of a spectrum market incorporating optimal pricing techniques similar to transportation congestion models is investigated. This study concludes by proposing a detailed mechanism for a limited spectrum market which is responsive to the user's resource input choice.

TABLE OF CONTENTS

I. INTRODUCTION

The spectrum is a unique natural resource. It is not confined by geographic or political boundaries. It cannot be exhausted through use, nor can it be worn out. When spectrum is overused it suffers from congestion just as water or air can be polluted by misuse or inefficient management. But, unlike other resources, once the cause of congestion ceases, the spectrum is completely reconstituted without appreciable cost. Unfortunately, the useful range of radio signals is much less than their interference range; transmissions do not cease abruptly at a fixed distance from the transmitter. Indeed, the transmitted signal is affected by constraints of natural phenomena which are unpredictable. Despite these idiosyncracies the resource of the spectrum has considerable application in modern society.

By administratively controlling spectrum use through government regulation, the Federal Communications Commission is the principal player in spectrum management for the commercial sector. The Commission decides who should receive and who should be denied access to the spectrum. Fueled by technological improvements, society's omnivorous demand for information has created an alarming scarcity of spectrum. Despite the value of spectrum to society as a natural resource and the rapidly decreasing supply, market considerations are not a factor in the Commission's spectrum management program. There exists no mechanism whereby the spectrum

like other resources can be purchased in the amounts required, nor can the right of ownership be transferred to an individual most willing to pay for it. Additionally, there is no value in not using spectrum because future returns will always be zero without any price-setting mechanism. Nevertheless, at the current time, there is no direct charge for use of the spectrum. Users have little or no reason to use it efficiently or to consider what others must give up when they use a particular portion of the spectrum. As a result, the spectrum is under-utilized in some portions and extremely congested in others. Moreover, there is no method which could reapportion spectrum use based on an individual's willingness to pay for an addition portion.

If a market for spectrum is created, it might give a better indication of what is given up when spectrum is allocated. The introduction of economic incentives in a spectrum market may cause greater allocative efficiency in spectrum use. This thesis proposes such a spectrum market.

By examining the current regulatory process and the allocation decision rules of the firm, a basis is provided for proposing a spectrum market. A simple description of the technical problems inherent in the propagation of electromagnetic radiation is given in Chapter II. A brief history of the current allocative method and its associated problems are presented in Chapter III. In Chapter IV, a few of the more significant spectrum market proposals are discussed. Chapter V investigates the firms production input choices

at the margin, the difficulties with externalities and transaction costs, and some parallels with transportation congestion models. From requirements derived in preceding chapters, Chapter VI proposes a limited market for spectrum allocation in s specific service. It describes a feasible plan whereby optimal resource allocation decisions can be made by the firm. The conclusion, Chapter VII, offers a summary of the market proposed and some final remarks on the need for improved spectrum management.

II. THE PHYSICAL NATURE OF THE SPECTRUM

A. ELECTROMAGNETIC SPECTRUM DIMENSIONS

1. Definitional Aspects of Spectrum

The electromagnetic spectrum is the set of all frequencies on which electromagnetic radiation is possible. Described by frequency, bandwidth, spatial volume, and time, electromagnetic radiation is characterized by a constantly expanding wave front, consisting of an electric and magnetic field at right angles to each other, which describes the boundary of some spatial volume in time [34, p. 438]. The velocity of wave front propagation for any frequency in free space is the speed of light. Although different frequency ranges of the spectrum possess different characteristics, i.e., sunlight, x-ray, radio waves, they all obey identical physical laws. Radiation is transmitted from a source, expands through space and time and that portion of the wave front incident to the receiver is captured.

Electromagnetic radiation is a form of wave motion with wavelength or frequency as the primary parameter. Wave length is the physical distance between the peaks of an unmodulated wave while frequency is the number of waves or cycles passing a fixed point per unit time period. This is usually described as cycles per second or hertz (Hz), after its discoverer. The set of radiated frequencies defined in hertz comprises the electromagnetic spectrum. These are generally arranged by frequency in ascending order from low

frequency radio waves up through visual light to high frequency gamma radiation.

The portion of the electromagnetic spectrum considered usable for communications is the set of frequencies from 3 kilohertz (KHz) to 3000 giga hertz (GHz). Of this set, up tc 275 GHz is currently allocated internationally and use of the radio spectrum above 300 GHz is restricted primarily tc research work [45, p. B-4]. It is clear that available technology imposes a constraint on the amount of spectrum available for practical communications applications.

The transmission of a single frequency is not sufficient for radio communications [57] purposes. To convey information, a range of frequencies must be used. This range is the bandwidth and is measured in hertz from the highest to the lowest frequency required. For each information-carrying application a certain specified amount of bandwidth is required. More about this characteristic will follow.

The time dimension of electromagnetic spectrum is relatively straightforwarward. Because radio waves propagate at the speed of light, a close approximation would be to consider them as instantaneously occupying a spatial volume. When transmission ceases, so does this occupancy.

The three dimensional physical space which radio waves occupy can be described only in a probabilistic sense. The volume of space occupied is a function of power transmitter, antenna design, the transmitted frequency and the

wave front propagation mode. The transmitted power determines the magnitude of the electric and magnetic fields comprising a radio wave. As the wave moves away from the source, the magnitude of the fields decreases. This attenuation is inversely proportional to the square of the distance from the wave front boundary to the source. In the case of an isotropic or point source, the wave front expands equally in all directions and the energy of the fields is spread over an ever increasing area. Then, at any distance from the source the energy incident to the receiver is only a portion, orders of magnitude smaller, than that transmitted. Equally important is that the energy not captured by the receiver continues on through space though at ever decreasing levels of energy [25, p. 36].

The shape of the volume occupied is to a large extent defined by the antenna. Antennas need not be omnidirectional; in fact, by focusing the energy into a narrow beam, greater transmission distances can be obtained because of the higher concentration of energy for a given transmitter power.

B. PROPAGATION

Radiation propagation reflects the unique nature of the earth's environment. The major portions of this environment which affect radio propagation are the atmosphere and the surface of the earth of which 71% is water, a highly conductive compound [18, p. 1-1].

The upper portion of the atmosphere is the ionosphere which is characterized by an increased concentration of free electrons caused by radiation from the sun. The radiation forms belts of increased ionization which can be distinguished by their relative free electron densities.

Sunlight and sunspot activity have a strong effect on electron levels so that these belts of ionization vary diurnally and seasonally with the amount of solar radiation incident to the ionosphere and cyclically with changes in sunspot activity. This solar activity causes the levels or layers to expand, contract and merge together.

While the height, thickness and electron density of each layer cannot be predicted in a deterministic manner, probabilistic estimates can be derived which provide some indication of actual ionospheric conditions. These estimates give an indication of radio propagation characteristics as a function of frequency and time [18, p. 1-2].

The propagation mode also defines the volume of space radio waves occupy. These major modes of propagation are line-of-sight, refraction, and surface wave. These are by no means an enumeration of all the technologically available alternatives.

1. Line-of-sight

In line-of-sight propagation the curvature of the earth's surface determines the maximum range of a system since the ground-based stations must theoretically be within sight of each other. Ranges of 30 to 90 miles are possible

but are dependent upon antenna heights and the intervening topography [18, p. 1-2]. The environment acts to limit the electromagnetic wave by absorption in the lower atmosphere and by refraction and multipath interference where two waves from two apparent sources can reinforce or reduce each other depending on geometry and atmospheric conditions. Precipication affects the use and reliability of the line-of-sight mode. If antenna height or directivity is changed, considerably longer distances are feasible and are directly proportional to the transmitted power.

2. Refraction

The refraction mode of propagation, commonly called the skywave mode, depends upon the ionosphere. The effective range depends on the angle of the wave incident to the ionosphere, the transmitted frequency, and the ionization level. As the wave front enters the ionosphere it is redirected and at suitable frequencies and layer altitudes this redirection is sufficient to return the wave to earth at a receivable energy level.

3. Ground Wave

Surface wave or ground wave propagation is used primarily in the lower frequencies where the radiated wave is propagated along the air-ground interface. At higher frequencies the wave is attenuated too rapidly for practical use. This mode is the most reliable and stable of all those using atmospheric transmission paths. However, it too is subject to interference.

C. NOISE

The level of noise incident to the receiver antenna is a major determinant in the ability to receive a transmitted radio wave. There are three basic elements of noise: naturally occurring noise, unwanted radio waves from other man-made sources, and internal noise [18, p. 1-1].

1. Natural Noise

Naturally occurring noise is received from outer space, the sun and from any other naturally occurring phenomena like thunderstorms. As seen by the fluctuation of the ionized layers in the upper atmosphere, the sun causes diurnal effects as well as cyclic effects. Cosmic noise from outer space is also a function of electromagnetic activity of other stars in space. The most unpredictable sources of noise are electrical disburbances in the earth's atmosphere. These effects can readily be heard on an AM radio during a thunderstorm. While technological improvements can minimize the effects of these unwanted signals, like FM broadcasting for radio, they cannot be halted.

2. Internal Noise

Internal noise is inherent to the design of the receiver. More technologically sophisticated equipments can significantly reduce these unwanted effects.

3. Interference

Incidental man-made radiation, commonly called interference, is the third major component of noise and is the least predictable. Interference of this type may

emanate from electrical generating stations, automobile ignition systems, or the citizens band buff in the neighborhood. Also, each radio transmitter generates a signal which can be considered as noise to someone trying to receive another radio station's signal [26, p. 36]. In each case, some unwanted electromagnetic energy has obstructed the reception of the intended signal, degrading to some degree the information content of that signal.

Three major forms of interference result from the transmission of electromagnetic waves [35, p. 210]. First, due to natural phenomena beyond the user's control, extensive and unpredictable patterns of interference result. Long range reception of AM radio stations is a prime example. Second, interference results from the unconfinable nature of radiation, particularly in regard to the technical problem associated with transmission. In this case, spurious harmonics or radiation at multiples of the intended frequency can be of sufficient energy level to cause interference. The third source of interference results from intermodulation products caused by simultaneous transmission at different frequencies in the same geographical area. While neither transmitter A or B alone could cause interference to C, if all transmit simultaneously, B causes interference to C while A causes no interference.

D. INFORMATION VALUE

Shannon's work on communication theory provides an explicit method for calculating the theoretical limit of the

information capacity of an electromagnetic wave [57]. Measured in bits per second, the amount of information transmittable is directly proportional to the bandwidth and the ratio of the signal and noise energies captured by the receiver. If greater information capacity is desired, the bandwidth of the transmitted signal or the power of the transmitter must be increased. This idea is simple enough, but the technical implications are much more constraining.

Emission bandwidth describes the size of the spectrum segment required for a specific frequency assignment [18, p. 2]. For example, a frequency assignment centered at 100,000 MHz with a bandwidth of 20 KHz would employ frequencies ranging from 99.99 MHz to 100.01 MHz. The bandwidth can be only a small percentage of the transmitted frequency because the various electronic components of the transmitter have only a limited frequency response. These components are designed for optimum efficiency at the transmitted frequency. At frequencies outside of the desired bandwidth, their efficiency is so poor that use of an increased bandwidth is technically impossible. Therefore, at lower frequencies, even though transmitter output may be on the order of millions of watts, only a very small bandwidth and hence, information capacity, is available. Conversely, in the Super High Frequency (SHF) range, those frequencies from 3-30 GHz, this same ratio may allow bandwidths as large as 500 MHz; however, extreme transmitter power

limitations, and the severe attenuation suffered by signals in this frequency range cause an appreciable reduction in information capacity. Because of the available bandwidth, the amount of information capacity of the higher frequencies is orders of magnitude greater than that available at the lower end of the spectrum [18, p. 2]. Hence, some degree of spectrum differentiation in terms of potential uses is possible.

The special characteristics of propagation mode and noise clearly illustrate the difficulty in defining the effects of electromagnetic radiation in other than a very probabilistic sense. The spectrum's multiple dimensions and ability for simultaneous use also provide some insight into the complex problem of efficient use. Being unable to completely solve the problem of spatial confinement by technology, some other form of control is required. Controlling interference is the fundamental justification for regulating use of the spectrum by allocation.

III. SPECTRUM MANAGEMENT

A. THE EVOLUTION OF CONTROL

1. Early History

In 1906, only ten years after Marconi was first able to demonstrate a practical method of electromagnetic transmission, and only five years after the first trans-oceanic telegraphy signal was received, the representatives of the industrialized nations met in Berlin to reach a common understanding in the use of electromagnetic spectrum [45, p. B-1]. In the early 1900's, the only frequencies that available technology could utilize were in the kilohertz range [25, p. 14]. Even low power signals in that portion of the spectrum can travel extraordinary distances by ground wave propagation. This fact, coupled with the poor quality of oscillators which controlled the output frequency and the equally deficient filters which allowed transmission of strong harmonic signals, caused interference problems despite the relatively small number of transmitters available [25, p. 15]. To avoid this problem of interference, new stations chose initial locations up to 50 miles from previously installed transmitters operating on the same frequency [25, p. 15]. Since the majority of users were maritime companies and large ships, choice locations were quickly obtained. By 1906, concern for safety at sea, interoperability, and intergovernmental use of the spectrum prompted convening the Berlin Conference [7, p. 2]. The international agreement

resulting from the conference was the first instance of spectrum allocation. Five hundred and 1,000 KHz were designated as the primary public service frequencies for ship-to-shore radio communication [45, p. B-3]. Despite rapid technological change and more refined allocation techniques, the 500 KHz assignment has remained to this day the primary international distress and calling frequency. In these formative years of international spectrum allocation the impetus for centralized control was not spectrum scarcity but rather frequency coordination, especially since there was an element of public good involved in the use of wireless telegraph. The distinctive feature of public goods:

> ....is that they can be consumed by more than one person at the same time at no extra expense; and it actually costs something to exclude potential consumers [37, p. 524].

A prime example of a public good is a television signal. Anyone living within the prescribed service area of the station can enjoy its programming at no extra expense to the station. Another example is the Coast Guard's weather service broadcast. It costs nothing for an additional subscriber and it would be nearly impossible to identify unintended users. This notion of public good is to pervade the entire regulatory history of the spectrum.

The problem was not one of finding a suitable frequency but was one of insuring that no one else had also found it. Since the major early application of radio telegraphy was maritime safety, regulations concerning mandatory radio equipment were quickly enacted [7, p. B-2]. The

obvious benefits resulting from international coordination could be easily measured in lives saved and cargoes protected. Government provided a central decision making authority which could oversee frequency assignments. Assignment decisions did not determine who should operate. Instead, they were concerned only with coordination. The decisions to specify services for particular frequencies were effected because the positive externalities of these decisions outweighed the potential negative effects of restricting the type of service available at a particular frequency. Positive externalities exist whenever the consumer is unable to capture all the benefits from a service [37, p. 13]. There was more than enough spectrum [25, p. 15]. Natural abundance made spectrum truly a free good.

2. International Telecommunication Union

The theme of international coordination has continued since those first foundational attempts at allocation. Under the eyes of the International Telecommunication Union (ITU), the amount of spectrum allocated for specific services has continued to increase up to the current limit at 275 GHz.

Essentially, the ITU provides an international forum for frequency allocation. To facilitate coordination, the world is divided into 3 regions [53, p. 166]. Each country in a region is allocated portions of the spectrum for specific services. International administration of spectrum allocation permits coordination of user services worldwide, especially air and maritime mobile applications. Requests

for additional spectrum are responded to on a first-come, first-serve basis. Actual use of the spectrum is not material to the allocation decision. Hence, there was considerable speculation prior to WARC 79 that emerging third world countries seeking parity with more industrialized nations would seek to stockpile spectrum in an attempt to provide future telecommunications security [53, p. 166]. Major shifts in allocation were feared because of the impact on capital investments. For the industrialized nations, huge expenditures would be necessary to change to new frequencies.

B. U. S. REGULATORY BODIES

As the need for some form of international cooperation increased after 1906, so too were increased problems affecting spectrum users within the U. S. Since wireless telegraphy was used primarily for maritime applications, the Navy became instrumental in guiding federal government policy, urging passage of a law "placing all wireless stations under the control of the Government" [7, p. 2]. While advocating their position, the Navy recognized "that such a law passed at the present time might not be acceptable to the people of this country" [7, p. 2]. The Navy's perceptions were correct; in 1912 Congress, fearful of bestowing "too great powers upon the departments of the government," passed the Radio Act of 1912 which required all radio stations on a first-come, first-serve basis, to obtain

a license from the Secretary of Commerce, stipulating operating conditions [7, p. 2].

Under Mr. Hoover, then Secretary of Commerce, a series of Radio Conferences, starting in 1922, were held to discuss the serious increase of interference caused by the fledgling but rapidly growing AM broadcasting industry [9, p. 17]. Operating between 535 and 2000 KHz, existing stations were suffering excessive interference because of the long range characteristics of that portion of the spectrum. Coordination was non-existent. In fact, various court decisions ruled that Mr. Hoover had exceeded his authority as defined in the 1912 Act and, by mid-1926, had insured governmental noncontrol by withdrawing any restriction over frequency choice or hours of operation [7, p. 5]. By 1927, the need for relief was acute. Indeed, during the period 1922-1924 alone, the number of broadcasting stations increased from 30 to 500 [46, p. 540]. In response, Congress created the Federal Radio Commission to coordinate interference and scarcity problems and to oversee the public good problem. Although broadcast listeners were beneficiaries of broadcasting, they had little say in programming decisions. It was thought necessary that, as the elected representatives of the public, Congress ought to impose programming restrictions on the broadcasters to insure that the interests of the public were served [7, p. 10]. The basic principles of this 1927 Radio Act became the foundation for the 1934 Communications Act. Created by this act was the Federal

Communications Commission (FCC) as an independent regulatory agency.

1. Federal Communications Commission

Under the provisions of the Communications Act, the Commission regulates all non-government telecommunications through a process of legislatively mandated rule making. The Communications Act specifically exempts "Radio stations belonging to and operated by the government" [45, p. C-1] from the provisions of the Act and provides that such stations will use frequencies as designated by the President.

> "The Commission is essentially faced with two basic responsibilities. First, we are charged with allocating and assigning radio frequencies so as to insure that orderly use is made of this valuable and scarce public resourse. Second, we are empowered to act as a surrogate for market forces in assuring that the price, quantity, and quality of telecommunications services offered by natural monoplies correspond with competitive market solutions" [24].

In meeting these responsibilities, the FCC divides spectrum management into three functional areas [10, p. 3]. First, the Commission allocates bands of the radio spectrum for the specific use of various services. Second, it assigns small segments of the spectrum within those bands to most individual users. Third, it details applicable technical standards and other user regulations pertaining to the legal use of the individual assignments. Each of these functions contributes in part to the overall regulatory effort of the FCC.

Allocation is a spectrum management function by which "the radio spectrum is subdivided into bands that

are reserved for providing different types of communication services" [10, p. 3]. This function recognizes the economies of scale and operational benefits derived from restricting the type of service offered in a particular allocation. It allows an orderly expansion of existing services by recognizing anticipated future spectrum needs. Also, by requiring a specific spectrum use within each allocation, the interference resulting from adjacent disparate users is hopefully avoided. Because of these characteristics, this management function is commonly referred to as block allocation.

Assignment is the administrative process by which individuals are licensed to use a small segment, a channel, or an allocation band of the spectrum [10, p. 5]. On successful application of an eligible individual, the Commission issues a license to operate and it also assigns a specific channel. Depending on the service, some assignments may be exclusive, e.g., television, or they may be shared with a number of other licensees as in the common channel land mobile service. Also, it is possible that more than one channel may be assigned a licensee for a particular application.

Technical regulation is intended to ensure technically efficient use of the spectrum and to control interference between users. Technical efficiency is controlled by establishing maximum acceptable levels of harmonic emission and by requiring that modulation techniques accommodate a minimum level of information carrying capacity.

Interference is controlled by requiring compliance with standards applicable to each license. Station characteristics controlled include power output, antenna height, and directivity, station separation distances, and authorized transmission times.

These three functions of the FCC are "carried out by rule making, using the notice and comment procedures specified by the Administrative Procedures Act" [10, p. 6]. No preference is given a prospective applicant in an uncongested service. Licenses are awarded on a first-come, first-served basis [10, p. 6]. However, in the case where an insufficient number of channels are available to satisfy all the applicants, the Commission resorts to formal adjudicatory procedures to determine the successful applicants. As various rulings are tested in court, a more comprehensive structure detailing spectrum applications is created. Hence, there is a complex interaction of technical, social, political, and legal requirements which dictates the nature of spectrum regulation by the FCC.

2. Interdepartmental Radio Advisory Committee

While it has been in existence since 1922, the Interdepartmental Radio Advisory Committee (IRAC) is less well known [9, p. 18]. Its genesis was a recommendation by the chairman of the first Radio Conference to then Secretary of Commerce, Mr. Hoover, that the government should also have an oversight body which could provide frequency coordination in the public sector [9, p. 19]. This was before the

Federal Radio Commission, the precursor of the FCC, was formed. In essence, IRAC serves as the governmental frequency assignment agency and consists of representatives from the major government agency spectrum users. IRAC receives policy guidance for strategic planning from the National Telecommunications and Information Agency (NTIA) which operates under the Secretary of Commerce. The NTIA, formed in 1977, is responsible to the President for issuance of frequency assignments.

Both IRAC and the FCC make use of the same National Table of Frequency Allocations which lists all frequencies by user categories. This table is in turn derived from the portion of the ITU Table of Frequency Allocation specific to the United States [45, p. B-6]. Both tables are under continuous revision. The national table reflects the current rulings of the FCC and NTIA, being amended as new rulings occur [45, p. D-1].

There is no formal mechanism for resolving competing claims between these two agencies for frequency assignment [9, p. 22]. Instead, an informal arrangement characterized by mutual cooperation provides solution to competing requests for identical assignments.

> "The Interdepartmental Radio Advisory Committee will cooperate with the Federal Communications Commission in giving notice of all proposed actions which would tend to cause interference to nongovernment station operation, and the Federal Communications Commission will cooperate with the Interdepartmental Radio Advisory Committee in giving notice of all proposed actions which would tend to cause interference to

government station operation. Such notification will be given in time for the other agency to comment prior to final action. Final action by either agency will not, however, require approval by the other agency" [9, p. 22].

While this statement may seem modern, it was made 40 years ago and fully illustrates the two bodies' desire for continued mutual cooperation. Thus, between the FCC and IRAC, the government regulates control of any portion of spectrum authorized by the ITU for use by the United States.

Today the nature of the FCC regulatory process continues unchanged. Assignments for all services are made subject to administrative regulatory constraints.

C. PROBLEMS WITH THE CURRENT SYSTEM

Since 1950 the effectiveness of government management in frequency allocation and application supervision has been the subject of investigation and criticism. The Communications Policy Board in 1950 attacked the split responsibility of IRAC/FCC.

> "Existing organization to control use of the spectrum, one of the most valuable natural resources of the United States, is responsible for the establishment or continuance of dual control of this resource. This dual control has led to friction, misunderstanding, waste and avoidance of responsibility. The organization is lacking in overall policy guidance, and is so complex that few persons understand all its ramifications" [51, p. 47].

They argued that spectrum allocation was being made under procedures which cannot weigh all the demands by government and commercial interests for spectrum use. The Board continued that it was impossible to make impartial judgements on fixed criteria with insufficient information.

Misallocation between government and commercial interest was criticized by the Joint Technical Advisory Committee (JTAC) in 1968 [28]. JTAC had misgivings about the division of allocation responsibility and the block allocation procedures [28, p. 24].

While the Charter under which JTAC operated "makes inappropriate the drawing of any conclusion as to the governmental organization necessary to provide these expanded spectrum engineering capabilities," the immense scope of the spectrum management problem was well understood [28, p. 73].

> Continuing enlargement of technical resources in microwave, personal radio, communications satellites, etc., has made practical a wide variety of radio communications. As a result, high density urban living, increased mobility of people at work or play, and our natural desire to keep in touch have brought us to the point where there are unsatisfied demands, conflicts and constraints in further utilization of the electromagnetic spectrum [28, p. 2].

> Finally, the point has been reached where we have to face up to the fact that the usable spectrum is a limited resource....The challenge lies in developing a new philosophy and new techniques in spectrum management that recognize this new administrative environment [28, p. 3].

The President's task force on Communications Policy concluded that efficient use of the spectrum was not being achieved primarily because the block allocation procedures were not responsive to the demand for spectrum [52, p. 8: 26-28]. Also criticized were the vague criteria available to the spectrum manager for resolution of conflicting claims. Under the 1934 Communication Act, allocation is to be made in "the public interest, convenience or necessity" [7, p. 13]. The task force argued that economic factors should be

introduced into the allocation procedure, especially in light of competitive claims, to promote efficiency and provide an economic evaluation of spectrum.

> Use of the spectrum should be subject to more direct economic forces in the future rather than being treated as a free right. It is of real economic value to the user which should be fairly reflected in allocation of the resource.....The direct beneficiaries should be called upon to bear a fair share of (the) costs. Economic incentives would also encourage users to apply their innovative skills toward more efficient spectrum use [52, p. 33].

While not a novel idea (it was novel to Adam Smith), the task force declined to mention how a spectrum market would be operated.

Two major characteristics of the commercial spectrum management system are:

1. It is relatively inexpensive.
2. It lacks flexibility and requires a long time to reach decisions [25, p. 19].

The FCC is inexpensive in terms of its budget, an argument which might be used to maintain the current system. However, this may be a tip-of-the-iceberg situation. The true social cost of spectrum management includes the opportunity costs of uses foregone by the block allocation system. Also, lengthy hearings generate significant transaction costs, not the least of which is the discounted value of idle spectrum. It is the entire economic cost which should be considered, not just budget expenses. The second characteristic correctly identifies the inability of the FCC to rapidly respond to technology change and, instead, maintain the vested interests of current users whether efficient or not.

These same criticisms are expanded by Agnew et. al. to four specific elements which describe the inefficiencies of current spectrum management [1, p. II-5]. They are:

1. Costs and delays of comparative hearings.
2. That certain portions of the spectrum have greater valuation in terms of use than other portions.
3. Less intensive or profitable use than is technically possible.
4. The "free good" aspect.

An additional fifth element concerns the subjectivity of the licensing procedure and the equity of the subsequent decision. All five elements are illustrated to describe current system inefficiencies.

1. Costs and Delays

The licensing procedure can consume an inordinate amount of time and prove costly. It is mandatory when two or more applicants seek the same assignment. A case in point is the application Mr. Buchner made in 1952 for ownership of Station WFTV in Orlando, Florida [13]. While the particulars read "like a soap opera," there is no denying that the inability of the FCC to reach a decision can be the source of economic aggravation by precluding any effective long run planning. A decision over the ownership of WFTV is still outstanding.

The costs of both legal representation in these administrative hearings and more importantly the social cost of unused but highly demanded spectrum are not reflected in

the FCC budget. These costs can be substantial even if the calculations are conservative. The costs of hearings are calculated as the sum of the hearing cost including all legal and staff fees and the value of the spectrum as lost profits discounted over the period the frequency assignment is idle [55]. Since transaction costs may differ with the number of applicants, whether actual hearings are held or a mutual settlement is reached among the applicants, it may be impossible to construct an algorithm for predicting costs. What is important, however, is that the regulation which is intended to reduce transaction costs may actually be causing an increase in such costs. On balance, it appears improvements can be made.

2. Differences in Spectrum Valuation

Under the current block allocation scheme, portions of the spectrum are set aside for specific use. The underlying reason is to deny disparate use of the spectrum in adjoining portions of the spectrum in an effort to reduce the interference from intermodulation or spurious harmonics. Hopefully, there is sufficient bandwidth in each allocation to satisfy all spectrum requirements. Unfortunately, the desired result is not always obtained. The effort by the land mobile users to obtain unused portions of the adjoining UHF-TV band illustrates the problem. Land mobile radio has shown a dramatic increase in demand to the point, almost, of necessitating hearings over competitive applications for already congested channels [6, p. 318]. Simultaneously the

UHF-TV allocation has many unused channels mainly because of the marginal profitability of many of these stations [4, p. 45]. What results is two adjacent portions of the spectrum differing greatly in valuation. It took ten years for FCC dockets 18261 and 18262 to reallocate more spectrum for land mobile use [22] [23]. However, the new allocation, made for the entire country, may not reflect the needs of a particular geographic area. The delay was necessary to insure that the correct portion of the UHF-TV allocation was transferred in the event the UHF-TV service became as profitable as once imagined [1, p. II-6].

3. Technical Inefficiency

In calculating the bandwidth of an assignment, the FCC determines the requirements of current technology before pronouncing its decision. In the case of broadcasting, the overriding concern may not be the amount of spectrum currently necessary for a service but rather the size of the current investment in receivers over which the broadcaster has no control. In broadcasting, once bandwidth is determined the number of stations in any geographic area can be determined given the bandwidth of the allocation [1, p. II-5]. The specific channels for each area are chosen such that the same channel is not occupied in an adjacent area. Hence, by determination of bandwidth, an absolute number of stations is derived. But, assignments are fixed in time while technology continues to improve.

Currently deliberations to decrease the bandwidth of AM radio stations from 10 KHz to 9 KHz are in progress. An ITU region II Administrative Broadcast conference is scheduled for March 1980 to standardize the AM broadcast assignment at 9 KHz for the region which consists of North and South America. Adoption of the new assignment would permit offering AM stereo while creating up to 140 new stations in the U. S. [5].

There are two reasons for the adoption of 9 KHz assignments. First, is to bring the Americas into agreement with the rest of the world which currently uses 9 KHz assignments. Border stations between two regions experience interference because of the different assignment spacing. Secondly, the FCC has over 5,000 applications for AM stations pending [5]. Decreasing the bandwidth would permit satisfying some applicants and allow some current broadcasters to upgrade their second class licenses to first class, essentially gaining frequency protection to permit greater transmission fidelity over a wider area [40].

Hence, while the system protects current users, it is not necessarily responsive to new technology. Succinctly stated:

> "Regulatory pressures alone, as we have applied them, are not enough to bring about the introduction and use of equipment designed to higher standards to conserve spectrum or to make expensive changes to benefit another user in the interest of efficient use of the spectrum....Regulatory pressure will never match the rewards that could come from self-motivated research stimulated by direct economic benefit" [45, p. A-7].

4. Spectrum as a "Free Good"

If a resource such as the spectrum can be consumed without cost by a user, then it is, in essence, a "free good."[1] The government's policy of no charge for spectrum use has undoubtedly intensified society's use of spectrum, but it has also served "to stifle individual motivation towards achieving more benefits in less spectrum space" [45, p. A-7].

It is reasonable then to assume that the user's choice of resource allocation will attempt to maximize use of the spectrum. Since there is no mechanism which relates the value of spectrum to its next best use, there is no indication whether use of the spectrum is optimal or if spectrum substitutes would provide a lesser cost alternative. An excellent example "is in television broadcasting, which provides the major substitute to cable television for distributing television programs to homes. A TV transmitter uses spectrum without paying for it; while a cable system must be built from costly resources. A consequence of the free nature of the spectrum is to make television look like a less expensive way to distribute programs than it really is" [1, p. II-7]. As shown in Chapter IV below, spectrum as a free good makes it imperative to obtain the least cost telecommunications equipment which typically uses more

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[1] A spectrum user could be an individual or a firm. In either case, utility or profit maximization would motivate allocation decisions.

spectrum than is required by currently available but more expensive equipment. Thus, the label "free good" is a misnomer; there is a cost involved. Whether it is the broadcasting station itself, the next best applicant for that station, or the listener who doesn't like the programming, who absorbs this cost is a matter of equity. What is important is the fact that the current administrative system of channel assignment is indisposed and ill-equipped to deal with the "free good" aspect of spectrum management.

5. <u>Subjective Determination of License Holder</u>

In broadcasting, the FCC awards a license to the "qualified" applicant best able to serve "in the public interest." Each license comes due for renewal every three years and the current holder may be challenged for possession by any applicant deemed "qualified" by the FCC. Basically, qualification entails being financially capable of operating the station and offering programming in the public interest [10, p. 8]. Once granted a license, unless moved by a desire to leave the industry, license renewal is almost a rubber stamp procedure. An example of an exception to this propensity is the recent FCC ruling that RKO General, a subsidiary of General Tire and Rubber Co., holder of 4 TV and 13 other licenses, is no longer "qualified." This opens the door to challenges for station WNAC-TV in Boston [62]. Three separate groups are in contention and each could become instant millionaires if awarded the license. RKO was unqualified because in the view of the commissioners, "the

company could not be trusted in the future to operate WNAC-TV in a manner consistent with FCC standards" [62]. The reason for RKO's fall from grace stems, apparently, from the parent corporation's problems in the early 1960's with the Securities and Exchange Commission, political slush funds, and overseas bribery charges. These difficulties were settled in a consent decree with the Justice Department in 1970. There was never any alleged misconduct on RKO's part, moreover the consent decree occurred three license renewals ago [64]. At the same time, Westinghouse Broadcasting was awarded license renewals despite the parent company's involvement in the notorious electrical price-fixing scheme [63]. General Tire and Rubber Co. intends to appeal the FCC's decision. This example describes the possible inequity resulting from difficult and expensive decisions. It also points out the potential capriciousness of subjective decision making.

Given these shortcomings of the current allocative method, recommendations to improve the responsiveness and efficiency have grown in number and come from two camps, the engineers and the economists.

The engineering approach is concerned with electromagnetic compatibility as defined by technical equipment specifications. Indeed, each license granted by the FCC contains the requirement to maintain strict adherence to technical specifications. By controlling the input function in such a precise manner the FCC provides an ad hoc

description of the probability of interference between adjoining stations [10, p. 4]. While not dismissing the importance of precise engineering or the need to continue technological improvements in electromagnetic compatibility, the emphasis in this thesis is placed on the economic aspects of the problem. Their approach is to remove or at least reduce fiat allocation and allow market forces to determine optimum allocations. Numerous proposals have been made to provide a valuation of spectrum based on market forces given that an excessive demand for a "free good" has overwhelmed the available supply or the FCC's ability to maintain assignment efficiency in the face of such demand.

IV. SPECTRUM MARKET TECHNIQUES

A. PRIOR CONTRIBUTIONS

Since 1959 when Coase published his article on the Federal Communications Commission there have been several proposals for instituting spectrum markets as a means for both valuing the spectrum and providing a more efficient allocative mechanism [1] [19] [21] [25] [31] [39] [41] [47] [54] [55] [66]. These proposals exhibit a broad range of characteristics. At one extreme the free market allows the license holder complete freedom of use for the spectrum he holds as defined by the property rights issued by the license. The property rights for spectrum use define time, frequency, and three-dimensional space as the criteria for determining the legal right to radiate. These output parameters constitute the legal limit of the owner's right to radiate while placing no restriction on the use of the owner's spectrum.

The limited market proposals as defined in this discussion are those in which the property rights of spectrum are more restricted and are defined in terms of input parameters or rights. In these proposals property rights are defined in terms of time, frequency and bandwidth, transmitted power and antenna height as surrogate measures of actual boundary radiation density. In most of the specific market proposals input rights are used in lieu of output rights because of the difficulty in defining or enforcing the latter. Regardless of the method of property right

definition, each proposal introduces economic incentives into the spectrum allocation process.

1. Free Market Proposals

While Coase provides no specific definition of property rights and it could be inferred what he really intended was the use of input rights; his work can be grouped in the free market category primarily because he makes a compelling argument for establishment of a pricing system in a spectrum market [7]. It is the first major work suggesting economic methods be applied to spectrum allocation.

Despite the absence of a formal recommendation, Coase's article is most important in recognizing the implications of transaction costs and externalities on the true social costs incurred by the establishment of spectrum market [7].

Minasian, in an extension of Coase's work, defines a set of rights which can be used in a market system [42]. As the scope of his work was primarily to provide a workable definition of property rights, no market recommendation is forthcoming. Minasian's set of property rights consists of four elements:

1. Emission rights
2. Admission rights
3. Use
4. Transferability [42, p. 232].

In essence, the owner is free to use his portion of the spectrum as he desires within the law, and he is able to sell all or part of his property rights. The major

distinction of Minasian's work is that the level of radiation at some radius from the transmitter must not exceed a previously agreed level of energy. The same type of conditions hold for the inevitable harmonics simultaneously transmitted. In addition, those who seek to use any portion of the right-holder's area would be limited to agreed-upon limits of radiated energy density to afford interference protection to the right-holder. As argued previously, the transaction costs of property right measurement might exceed the benefits gained.

DeVany et al. offer a more specific property right definition. They postulate a Time, Area, Spectrum (TAS) algorithm for property rights which essentially is an extension of Minasian's work [19]. This use of TAS units reflects a considerably greater emphasis on the technical problems of radiation transmission and associated interference. The resulting definition of output rights forms the basis for the four specific recommendations for spectrum markets in the UHF-VHF bands which concludes the work. These proposals are:

1. Use of alternate VHF and intermediate UHF television channels.
2. Clearing of adjacent UHF television and land mobile channels.
3. Vesting FM broadcast rights.
4. Packing FM stations [19, p. 1537].

Each of these proposals is intended for experimental use in demonstrating the adequacy of the TAS units in creating a spectrum market.

2. Limited Market Proposals

Limited market proposals have been more prevalent in recent work primarily because of the problems in adequately defining property rights. The limited market proposals use input rights to describe the property rights of the license holder. Each proposal is restricted in scope to a particular service, recognizing the difficulties associated with combining different services in the same band.

The principal proponent of the limited market idea is Levin, whose book The Invisible Resource and numerous papers, are a major effort to establish the need for economic incentives in spectrum allocation [31] [32] [33] [34] [35]. Discussing the economic aspects of spectrum use in detail, he advocates treatment of the spectrum in an economically efficient manner. In addition, he examines the use of shadow prices, auctions and calculated spectrum usage fees as a price mechanism for spectrum allocation. Levin argues the impracticality of specific property rights, like the TAS units proposed by DeVany et al. He concludes that usage fees and spectrum shadow prices as economic techniques should receive greater consideration in establishing an economic valuation of spectrum. This, in turn, would create a greater incentive to conserve spectrum use than would administrative allocation.

While Levin provides the most expansive treatment of limited markets for spectrum, there have been other significant efforts to describe specific markets for application of economic techniques.

Jackson makes four market proposals, the most significant of which recommends a market for the geostationary orbital slots of communications satellites [25, p. 71].

It consists of two main features: a defined orbit-spectrum right and an auction of satellite slots. Both features are organized under international aegis. The geostationary orbit is divided into "segment shares" (SS's) which are auctioned [25, p. 76]. Each satellite is defined in terms of a "spacecraft right" (SCR) [25, p. 79]. Measured in degrees of arc, the SCR for any satellite is determined so that the satellite neither causes interference with nor is interfered by a "standard satellite" [25, p. 80]. Once the size of the SCR is determined, then sufficient number of SS's are obtained at auction prior to registration with the International Frequency Registration Board (IFRB), the recording agent for the ITU. The market proposed allows only rental, not sale, of SS's to discourage future inefficiency and to make spectrum prices more visible.

Agnew et al. take exception to some elements of this proposal and restate them [1, p. XII-2]. Specifically, they argue that SCR must be defined not only for systems homogeneous to the standard satellite, but also for new technology which should not be restricted for the sake of homogeneity [1, p. XII-4]. The SCR's they propose differ for broadcast and fixed service satellites. Essentially, the SCR consists of a segment of geostationary orbit, a geographical service area, and a frequency band defined for

every satellite in the 12/14 GHz and 20/30 GHz band. In addition, they propose that the duration of the grant be indefinite, and that segment shares be fully transferable to qualified operators [1, p. XII-9]. They continue with an analysis of their modified Jackson Plan.

The modified satellite plan presented by Agnew et al. is only part of a lengthy survey of economic techniques for spectrum management [1]. In addition, they present three other spectrum market methods and an analysis of each. These techniques are frequency coordination, a license auction system for multipoint distribution service (MDS), band assignment in land mobile radio, and the satellite orbital slot mentioned above.

The frequency coordination technique is actually in use but not widely recognized as an economic incentive to more efficiently allocate spectrum. In frequency coordination, a potential entrant to the terrestrial microwave or fixed satellite service in the 4/6 MHz band must obtain an agreement among all current users that his entry in a specific geographical area will cause no unacceptable interference. If interference will result, the newcomer can choose to install interference shielding, redirect his antennas or he may pay for any equipment modifications or additional interference shielding at the interfered station. Since the number of stations is limited, negotiations are relatively straightforward and allow prospective operators entrance to the market after interference reduction costs are born by the newcomer.

In the MDS proposal, the major issue is whether auctions as proposed by Robinson or a lottery would prove less costly than the public hearings now used for determining the successful applicant [55]. MDS is an interstate common carrier service in the microwave band, broadcasting multiple-addressed material to fixed receivers. Their analysis concludes that the English auction system provides a Pareto-optimal least cost solution [1, p. VIII-16].

The band assignment model is an elaboration of a previous proposal by Dunn and Owen [21]. It is characterized by the auction of bands which have bandwidths two or three times that of current mobile channels. The successful bidder has exclusive control over his band assignment allowing operator choice of technology and usage. The licensee is subject to out-of-band and out-of-area interference standards like the technological specifications now required by the FCC. Transfer of the license in whole or in part is allowable.

Each of these market proposals deals with a specific portion of the spectrum, uses input rights to define the area irradiated and provides a scheme for payment of spectrum use. Without so stating, these proposals recognize the unsuitability of spectrum substitution. That is, for a given application or service only certain frequencies are acceptable. Hence, the creation of a single spectrum market is infeasible because there are essentially different commodities, i.e., spectrum applications, being marketed. Also, by segregating spectrum markets the technological problems

associated with modulation incompatibilities caused by disparate uses are avoided.

B. METHODS OF SPECTRUM PRICING

Spectrum pricing methods fall into two basic categories. In the first group are user fees. The second group consists of auction systems. Each method attempts to capture the users' willingness to pay in setting a market valuation of spectrum.

1. User Fees

User fees are administratively determined charges levied on the spectrum consumer. They can be determined by fee formula or by an approximation of shadow prices.

Fee formulas, in general, attempt to capture the spectrum users' willingness to pay for spectrum in a mathematical formula. Using area served, bandwidth, channel capacity, power density or other values as variables, a fee is derived which hopes to equate the consumers' marginal willingness to pay for each assignment. Fee formulas have received some consideration in House and Senate proposed rewrites of the 1934 Communications Act [1, p. IV-18]. There are two difficulties with this method. First, the fee formula must be correct to optimize efficiency and secondly, determining the value of the constant term found in each formula is extremely difficult [1, p. IV-17].

The broadcaster fee formula $F = aBN$ illustrates the point [66, p. 65]. Here a is the constant and B is the bandwidth in MHz. N is the population in millions receiving

the signal or excluded from receiving another signal on the same frequency. (The value of N assumes an a priori determination of acceptable reception.) Unless there is some external goal, i.e., minimum acceptable revenue, the value of a is indeterminant [1, p. IV-2]. Indeed, its choice requires that the marginal productivity of the bandwidth in question be predetermined, which is what the pricing mechanism is supposed to provide.

Shadow prices are derived from the maximum sums that spectrum users are willing to pay rather than do without some additional amount of bandwidth [35, p. 215]. The calculation of shadow prices requires estimating opportunity costs of alternative spectrum uses. It allows price estimation without any actual payment occurring. Once calculated, the spectrum manager allocates spectrum based on these shadow prices. While intuitively appealing, difficulties do arise. First, the information necessary for calculation of shadow prices may be inaccurate, non-existent, or too costly to obtain.

Also, there may be disagreement over whether the shadow price reflects the willingness to pay of the profit maximizing user or the market as a whole [2, p. 19]. Two distinct definitions of shadow price must be considered. There is the firm's shadow price (the value to the firm of an additional unit of input) and the market shadow price (which represents the price of the input if it were on a competitive market). The firm's shadow price is what Levin

uses in calculating "a set of charges on occupied bandwidth" [31, p. 118]. Because of the diverse supply and demand schedules of individual firms, it may not be practical to find an average value for determining the market shadow price. This is true because of the wide variation in spectrum valuation under regulation; to the firm with more than enough spectrum, its value may be essentially zero, while the firm which needs more or is excluded from using spectrum may value it highly. Additionally, inter-allocation spectrum transfer would necessitate continuous recalculation of the market shadow price as the market seeks equilibrium [2, p. 18]. This would compound the difficulty in translating the firm's shadow price into a market shadow price in a market which may not exhibit all the characteristics of perfect competition, i.e., a change in supply may affect price.

2. Auction Systems

Auction systems have been proposed as a method of placing the responsibility of price determination on the user. An auction provides a potentially Pareto-optimal mechanism for separating the indifferent user from a financially committed one [56, p. 489]. The actual auction technique may vary. A Dutch auction, where the highest bidder pays that price or the English method, where the highest bidder pays the second highest bid, may be used [61, p. 8]. Bids may be oral or sealed. Whichever the case, the winner pays the government and obtains the license. However, in

most cases, the license is not issued in perpetuity and must be offered in public auction at some predetermined point in time.

The stratified auction provides for bidding only within a particular allocation [35, p. 216]. No interband bidding is allowed. This method deals with the interference problems caused by allowing technologically different users access to proximate portions of the spectrum. From the results of the auction, a shadow price representative for that portion of the spectrum is obtainable. With relative intraband auction values available, the spectrum manager could reapportion spectrum allocations to avoid inequitable or socially inefficient use.

Regardless of the market mechanism or price determination method chosen, it is essential that a proposed system offer greater efficiency than that currently in operation. A viable market must cause the spectrum user to fully internalize the social costs of spectrum use.

If a market is initiated, the transaction costs of doing business must be minimized to permit active participation. Indeed, it is in part, because of excessive transaction costs, that regulation becomes necessary [29]. Implicit in a market is the nature of property rights and the freedom of use that the right-holder enjoys.

The object of introducing economic techniques into spectrum allocation is to improve social efficiency. A positive price for spectrum use characterizes these

techniques. It is important that the market allow the individual firm the freedom to choose the amount of spectrum necessary for efficient production. If each firm is afforded this opportunity to make optimal resource allocation decisions, then in the aggregate the market will be optimal. This requires that each firm recognize the marginal social cost of spectrum use. It is also necessary that certain characteristics be evident in the market. These are discussed in the following chapter.

V. ECONOMICS OF THE SPECTRUM MARKET

A. LIMITATIONS OF SPECTRUM SUPPLY

The spectrum is becoming an increasingly scarce resource. Demand continues to increase for new assignments while the supply of spectrum at any time is a function of available technology. The scarcity problem is exacerbated by the administratively controlled block allocation system which dictates the level of technology usable for a given service. This is especially true in broadcasting where the bandwidths of each channel assignment have remained essentially unchanged since the service was first adopted.

The available supply may be increased by two different methods. The first method is accomplished administratively. By changing the amount of spectrum allocated to a particular service, increased supply can be detailed to one service at the expense of another. The total supply is certainly not enlarged, but by shifting allocations it is possible to increase the supply of spectrum for a heavily demanded service. Such expediency is only a short run appeasement of demand and cannot in the long run provide an acceptable source of supply. This action is in part a response to an artificially high demand caused by administratively leveled constraints on spectrum use through the current allocation process.

The other method to increase spectrum supply entails the use of technology to increase both the "extensive" and "intensive" margins of the spectrum [31, p. 19-24]. The

former involves expanding the amount of spectrum available, while the latter permits more users to occupy the same amount of spectrum now available. The "extensive" margin has shown dramatic increase in the past 70 years. In the early 1900's the maximum usable frequencies were about 2 MHz. By 1980, technology has improved to allow use of frequencies above 300 GHz, an increase of over 150,000 percent. Improvements continue to be made and new regions opened for commercial use.

On the other hand, development in the intensive margin seeks to increase the number of uses in a fixed bandwidth of the spectrum while maintaining an acceptable level of interference. Interference and noise will never be eliminated, but technology can control its impact on the user's ability to provide a telecommunications service without suffering intolerably high levels of interference. Any sort of technological improvement which gives a better probabilistic estimate of the spatial volume occupied by a radio wave creates greater spectrum capacity in a geographical sense. Also, bandwidth reduction techniques, which improve information capacity, permit more consumers to occupy the same amount of spectrum bandwidth. These are improvements in the "intensive" margin. Driven by technology, the expansion of both the extensive and intensive margins has been impressive. However, the demand for spectrum has increased disproportionately to the increase in supply due, primarily, to the dramatic decrease in electronics costs. Technology

is a two-edged sword; on one hand it contributes to a greater spectrum supply while, on the other, it provides an accessibility to the spectrum unmatched in history. The pace of recent developments in reducing cost does not seem to be faltering; if anything, it is providing greater opportunities for access. At some point demand will exceed supply and serious congestion will result. This argument is not new.

> "(The Navy) has for years sought the enactment of legislation that would bring some sort of order out of the turbulent condition of radio communication, and ... it would favor the passage of a law placing all wireless stations under the control of the government..." [7, p. 2].

Serious congestion or spectrum pollution will preclude making assignments to new applicants and will cause dissatisfaction within the ranks of previously licensed operators. Even though spectrum is now available at no rental cost to the user, once excellent service is obtained it becomes an assumed right that such conditions of service will persist.

In addition, under the current block allocation scheme, specific uses are required in each allocation, and license transferability is denied. The administrative mechanism forces opportunity costs on spectrum users which could be ameliorated if market incentives were applied to properly value spectrum use. Concomitantly, the congestion problem would decrease.

If a licensee no longer desires to use the spectrum, that assignment should be made to another who values it more highly. There is no simple market mechanism whereby a licensed operator may transfer his license or part of it to

another [10, p. 19]. Nor may the licensed operator decide to use that portion of the spectrum for a use other than that for which the license was issued, despite his ability to realize a higher rate of return on his investment were the latter alternative chosen. By conforming to current practices, the operator's decision is socially inefficient, as the opportunity cost is the profit difference of the two alternatives all other things being equal. Likewise, if another individual were able to obtain greater efficiency through his application of that same portion of the spectrum than the present license holder, then he should be able to purchase the license. The value of the spectrum to the purchaser would determine the price. Similarly, if the original licensee decided that he required only a portion of the spectrum he now held, then to optimize spectrum usage he should be permitted to sell the unused portion to one who could provide a greater return on its use.

Allocative efficiency requires that only the most profitable choices of spectrum uses be undertaken. In the light of regulatory inefficiency it is necessary to determine if, in fact, a market can perform as well. Essential elements of the market must exist and the benefits gained must outweigh the costs incurred by market imperfections.

B. RESOURCE ALLOCATION IN A SPECTRUM MARKET

1. Market Factors

Given a purely competitive market, an efficient price system can produce an allocation scheme whereby no

reallocation of the resource can benefit one individual without doing some disservice to another. Such Pareto-optimality is the goal of an allocative mechanism. Moreover, the use of price as an incentive allows the individual to set a valuation on the amount he or she is able to utilize vis-a-vis the gains foreseeable in another investment. In the context of the market, the price of a commodity provides information on society's valuation of the commodity and provides a self-adjusting mechanism which accommodates changes in technology, substitutional effects, and consumer choice.

Any allocative scheme based on economic techniques must consist of at least 3 basic elements; with any omissions the market would fail [1, p. III-2]. First, the resource in question must have a positive price. At zero price, demand will decrease only when attempts to use the resource are frustrated by extreme congestion. As an example, there is no value to the user to enter a freeway where the congestion is so great that travel is made impossible. There is no incentive to use the resource because the resource, i.e., the capacity for high speed travel no longer exists. The next best alternative is then chosen. With the institution of a positive price there is a tangible reward for using less of the resource.

Given a positive price, time ordered investment preferences can be made. Investment choices are based, in part, on net present value. That is, the time stream of future returns discounted at an appropriate rate must exceed the

present and future discounted costs. In the case of spectrum it may be less costly for the user to defer purchase rather than obtain it now and use it inefficiently. Similarly, based on a time valued preference ordering, it may be less expensive to purchase spectrum now and hold it for future use. Regardless of the investment strategy adopted, a positive price permits individual choice over time.

Implicit in this price system is the role technology plays in determining price. A spectrum market would allow the user to make a rational choice of spectrum quantity and equipment technology. If a full range of technological options are made available to the consumer, he or she should be afforded the opportunity to determine on an individual basis the amount of each input resource for profit maximization.

A second major element is the need for a mechanism to determine an optimum price. This mechanism is the market which must allow a free exchange of information to all potential entrants. It must attempt to provide an accurate reflection of all social costs involved, minimize transaction costs, and accommodate changes in technology and consumer demand.

The third major element is the degree of freedom provided by the market for the transferability of the resources. The original owner may no longer realize an acceptable rate of return on his investment, while a potential owner may be able to earn a higher return. Then, maintenance of efficient

resource allocation dictates that the user's rights be transferred to the new entrant. Limiting transferability would require the original owner to make costly adjustments to maintain an acceptable level of profitability and require him to forego other more profitable investment opportunities.

2. Spectrum Input to the Production Function

To more fully appreciate the degree to which an administrative allocation method affects the manner in which resource allocation decisions are made by the firm, it is necessary to investigate the firm's decision rules for profit maximization at the desired quantity of output. If the firm is in the telecommunications business, the production function can be characterized as:

$$Q = f(K,S)$$

where Q is the quantity of telecommunications service provided,

S is the amount of spectrum utilized, and

K is the amount of all other inputs and represents capitalization, labor administrative and development costs, etc. For purposes of this discussion a rigorous definition of spectrum units is unnecessary; a unit of spectrum can be considered as a portion of the electromagnetic spectrum described by frequency and bandwidth. This is not to say that in a practical market scheme a more rigorous and legally acceptable definition may not be mandatory.

Certain basic assumptions are necessary. The first is that the firm, having chosen a desired level of output,

will rationally opt to minimize total production costs. Secondly, the production function is assumed to be concave. The last, but perhaps most important, is that social costs are fully internalized. This is a necessary condition for minimization of social cost.

Figure 1 depicts the isoquants of the production function Q_0 - Q_4. The ridge lines R_1 and R_2 are the boundaries of the set of all technically efficient production possibilities. That is, for any point on an isoquant within the ridge lines it is impossible to produce more output without an additional amount of at least one input. S_c represents a constraint imposed by technology on the amount of bandwidth employed and is determined by what is currently technologically infeasible, not by any social equity or legal constraint.

The firm's total cost function is given by: TC = f(nk, ms) and is assumed to be linear for this discussion where n and m are the costs for a unit of k and s respectively. The slope of the total cost curve is given by $\partial K/\partial S$ which also represents the marginal rates of substitution. This is the rate one input may be substituted for another while maintaining a constant output. Two isocost curves are represented by C_1 and C_2. In the case where spectrum use has zero cost, M = 0, the isocost function C_1 is completely elastic. The obvious choice for a profit maximizing firm is to use inputs in the amount of K_1 and S_1 as determined by the point on Q_2 tangent to C_1. In this

Production Isoquants

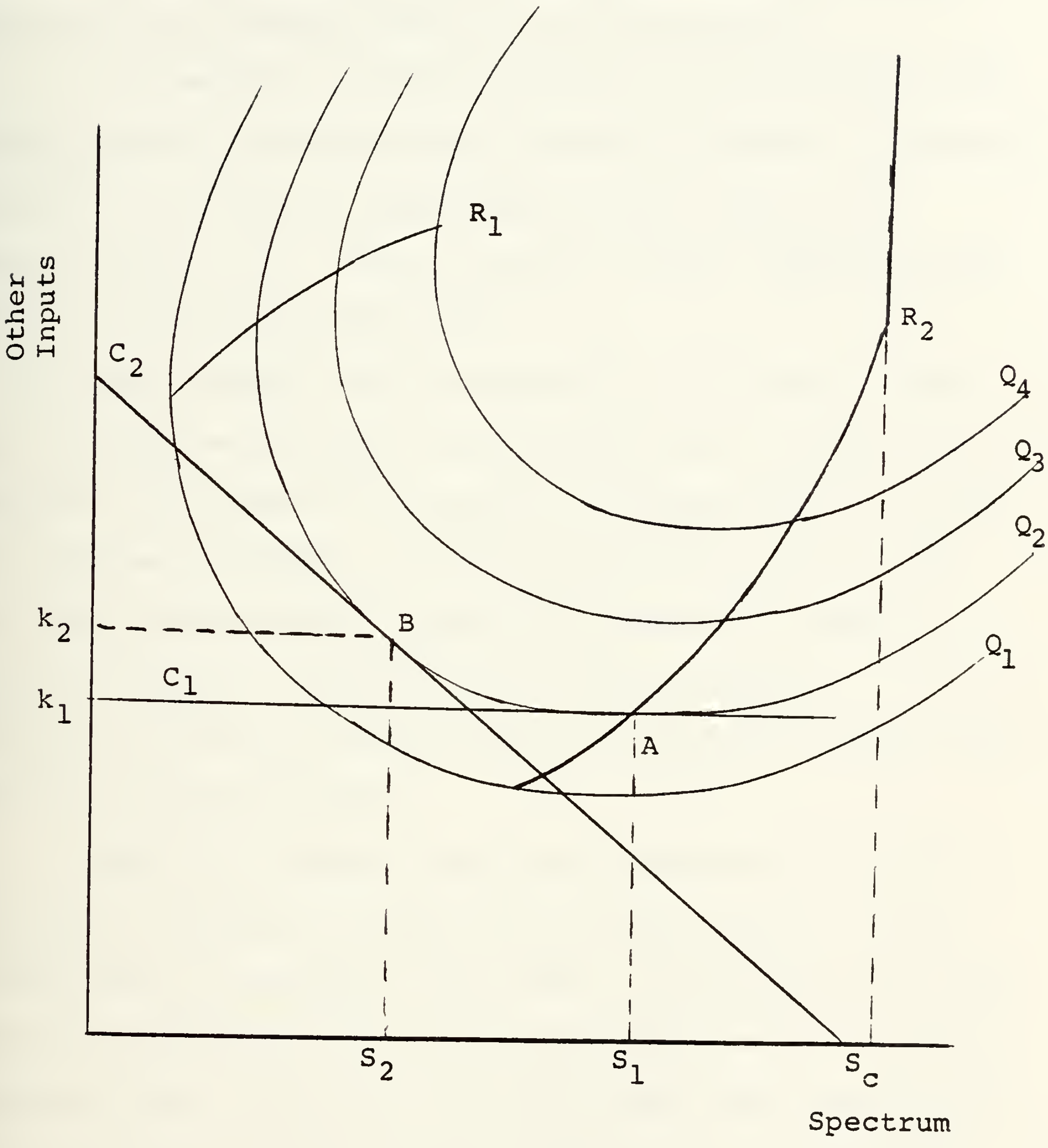

Figure 1

case, choosing point A is both a technically and economically efficient operating point. No other combination of inputs can produce Q_2 units of output at any lower cost.

If, however, a positive price is imposed on the use of the spectrum, some different mixture of inputs is required. For $n \neq 0$, C_2 is the corresponding isocost curve with tangency to Q_2 at B. Then K_2 and S_2 are the required input amounts for economic efficiency.

This argument can be expanded to show that as the cost of spectrum increases, there should be a corresponding decrease in the amount of spectrum utilized while the amount of K utilized increases. The rational firm will seek the least cost combination of inputs to produce the desired amount of output. Concomitantly, for any number of technologically efficient solutions there is only one economically efficient operating choice.

Under the current regulatory practices of the FCC the choice of inputs is restricted by prior determination of the amount of spectrum to be used. This is done by both the block allocation scheme and the channelization of that allocation band [10, p. 3]. For the profit maximizing firm, input decisions are made along isospectrum curves and the true costs of production are not reflected in the choice of remaining inputs.

The FCC regulates spectrum usage by defining the amount to be used. This amount is represented on Figure 2 by S_r and is an administratively determined input constraint.

Regulatory Effect

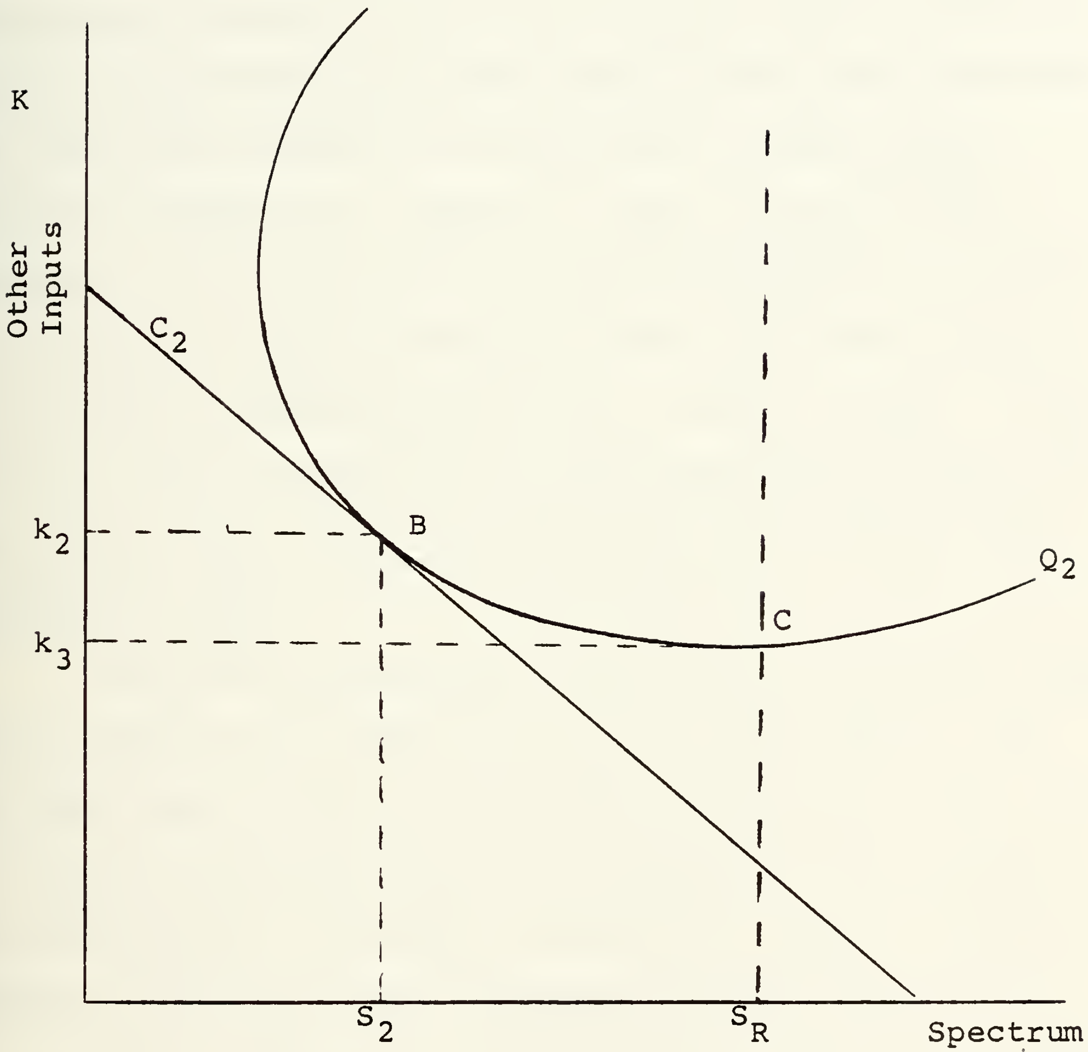

Figure 2

Also, for all practical purposes, if the cost of using this predetermined amount of spectrum is zero, then the firm will operate at point C and utilize k_3 amount of other inputs to produce an output of Q_2. It is obvious that this amount is technically efficient, but is it socially optimal? Because the use of spectrum causes some social costs to be incurred, then these must be born by those firms excluded by the licensing procedure of the FCC. Only if point B and C coincide, will the costs of k be socially optimal. This is not the same as saying the use to which this firm will put its portion of the spectrum will be socially optimal. Also, if $B \neq C$, then a valuation of inefficiency can be given by $n(k_3 - k_2) - m(s_3 - s_2)$ where the social cost of spectrum occupancy is used.

Given the bureaucratic nature of any regulatory body, it is reasonable to assume that S_R will not equal S_2 and that some misallocation of resources exists due to the lack of a market determined price for spectrum. Since the regulator must rely on imperfect information from all firms involved in that particular telecommunications service, the position of S_R reflects an average value. Implicit in this position of S_R is some level of technology which each firm possesses or is able to acquire at a reasonable price. Given the rapidly declining costs of new electronic equipments and the slow administrative procedural method by which FCC divisions are made, S_R is to the right of S_2 and that given complete freedom of choice the firm could make a more optimal allocation decision.

Two major opportunity costs which underly this discussion are the cost of unused existent technology and the cost to society incurred by denying license to a petitioning firm on the basis of insufficient spectrum. Because regulation attempts to reduce transactions costs by replacing a failed market, it is important that these two opportunity costs are not greater than the transaction costs saved by regulation [15, p. 12]. Further, introducing market incentives, i.e., price, may lead to a more socially efficient solution than that realizable under regulation.

As Jackson states:

> "We have a system suited to an era of slow technological change. It is a system which works best with a relative abundance of spectrum resource. And it is a system designed with great concern for the public goods aspect of resource use" [25, p. 19].

To obtain an efficient price for spectrum, the true social cost of spectrum must be calculated. But due to the nature of spectrum externalities, the problem with defining spectrum property rights, and the problems with transaction and enforcement costs, setting and efficient price may not be a simple matter.

Because there is no valuation placed directly on the use of spectrum, it is difficult to assess the opportunity costs which are directly tied to the transferability and use of a portion of the spectrum. To adequately incorporate the problem of transferability into a market mechanism for spectrum allocation, and, indeed, to even establish a market, some acceptable definition of spectrum property

rights must be proposed. In addition, problems with externalities transaction costs, and enforcement costs must be minimized to allow the market to function effectively. In a spectrum market these are difficult issues and each must be squarely dealt with.

C. MARKET IMPERFECTIONS

In the previous section production input decisions were investigated under conditions which assumed that all externalities were fully internalized. This obviously is not the case even in a market which is commonly termed competitive in everyday usage. There will always be departures from the optimum market conditions. In the case of a market dealing in spectrum usage rights these imperfections may be severe enough to cause market failure. The imperfections dealt with here are definitional problems of property rights, externalities of transmission, transaction costs, and enforcement costs. Each is discussed to obtain an understanding of the limitations in a feasible spectrum market.

1. Property Rights

As a result of market action, the legal acquisition of a good conveys certain property rights on the owner. Exercising the right of ownership can produce externalities which are harmful or beneficial to others. What is of concern here is that an efficient solution be reached whereby all costs and benefits of utilizing the good are borne entirely by the owner. Liability for one's actions determines only the responsible party, and the degree of freedom

with which he may exercise the rights of ownership. It does not determine the efficient solution [8, p. 8]. Illustrating this point is Coase's example of the farmer suffering crop damage from the roaming cattle of the neighboring rancher; Demsetz states:

> "Coase points out the efficiency of the solution with respect to the number of cattle and the size of the crops in the absence of exchange costs is independent of whether the farmer or rancher is legally liable for the damage" [15, p. 12].

A legal statement of liability is necessary only to determine the course of action one party should take against another. The prime concern is to produce a socially efficient solution given that externalities exist [15, p. 12].

At best, electromagnetic radiation can be described in a probabilistic sense. First, there is the difficulty in defining the energy density at the wave front boundary as it moves through space. Since air, water vapor and rain can each cause some variation in attenuation, the relationship of attenuation to the square of the distance is only a close approximation. Second, the propagation made can cause any number of realizable paths given any set of frequencies and atmospheric conditions. Third, is the effect of noise on the signal, specifically man-made interference over which some control may be exercised. Therefore, if the propagation path of a radiation wave is so ill-defined, how can property rights for spectrum be defined to permit an efficient market mechanism for spectrum allocation? It is important to define at the outset what is involved. First, there

is the ownership or control of a good. In the case of spectrum control, the owner may choose to use or not use spectrum for any purpose as he sees fit. If by not using it he can realize a greater return then he should do so. Secondly, he exercises control over its use in some manner which may produce "side effects" or externalities. Harmful externalities are interference to others. Right of use in this case leads to a choice over the extent to which externalities may be inflicted on others, either knowingly or unknowingly [8, p. 15].

Defining property rights for spectrum is not a straightforward problem. In most descriptions of property rights the commodity is some tangible good; here two or more people, given the appropriate technology, may be able to utilize identical portions of spectrum. The idea that there must be some strict geographical demarcation of ownership is not a valid argument.

Use of the spectrum can create externalities which must be taken into account in describing the limits of freedom for the property owner. In the case where the owner is completely free to do as he chooses the resulting chaos could be catastrophic to the industry, creating what has been termed an "anarchy band" [26, p. 39].

Minasian lists four conditions which define a set of property rights which would adequately incorporate the necessary economic attributes. These are:

a. Emission rights - the right to transmit with specifically defined radiation output characteristics.

b. Admission rights - the right to refuse use of the spectrum to another whose transmission would occupy the same dimensions specified in the emission rights.

c. Use - freedom to choose the type of legally available service which best suits the owner's needs.

d. Transferability - as with other resources, the rights both of emission and admission either in whole or in part may be transferred at the discretion of the owner [42, p. 232].

DeVany et al. expand on these rights, providing greater recognition of the technical problems but basically the two definitions are similar [19, p. 1512-29]. The latter two are acceptable; however, there are some problems with the first two. Concerning emission rights, the costs of measuring the field density at any point in space may exceed the gains of specific ownership. Since the energy density of an electromagnetic wave at any distance from the source is not easily quantified, a measurement system may prove too costly to provide an accurate description of the effects of transmission. This is especially true since the electronics industry characterizes its equipment by input specifications of transmitter power, frequency and

antenna patterns. A whole new radiation measurement industry would be required to adequately monitor all transmitters.

The problem with the second point is in determining the source of unadmitted radiation. If some cost will be incurred by not transmitting, then it is in the interest of the interloper to transmit if the costs incurred in satisfying the legal owner are less. However, if he cannot be identified or if the cost of identification exceeds the gain in reparation the owner may seek, then the interloper should continue to transmit. This does not mean that if he is identified, he will avoid the courts but it does point out the problems associated with defining a property right which may not prove acceptable from a social efficiency point of view.

An alternate proposal not as all encompassing as Minasian's, but which is much easier to accept is one where transmission rights are stipulated in terms of the current license. The current procedure requires that the equipment the licensee intends to operate must meet certain technical parameters. While such a proposal avoids the measurement costs of determining boundary energy densities, they none the less can, given an approximate probability function for noise and propagation mode, yield a prediction of boundary energy density. Measurement of such input parameters is part of the study of electromagnetic compatibility and is recommended by JTAC and others as a means of coping with the interference problem [27]. This proposal is

closely aligned to that of Levin and Cornell. Levin's apprehension over an explicit definition of rights is based in part on the difficulty involved with propagation prediction and the effects of spurious emissions [32, p. 91]. Cornell's proposal is based on the sheer practicability of continuing a well-defined system of insuring technical competency in radiation transmission [10, p. 15].

The other essential feature of a system of rights is transferability. The holder of rights must be free within the law to dispose of his goods in the manner he alone decides. It can be argued that for the greatest efficiency, the holder should be allowed to transfer those rights in part or in whole. If the current administrative system were to be replaced by a market system, such freedom of choice must be made available.

The important feature of any rights system is that it must provide a framework under which a determination can be made which decides who is liable in the event liability claims are made [16]. Under such a system it is shown that liability is not material in determining efficient allocation [15, p. 12]. Some discussion of the externalities is necessary for understanding their implication in the prices and costs of a market.

2. Externalities

The benefits to society from the positive externalities of spectrum allocation are straightforward. They include maritime safety, international connectivity, air

mobile (aircraft coordination), mutual coordination of broadcasting frequencies, and world-wide radio navigation systems, etc. These benefits are well-recognized, easy to characterize, and should be preserved by an allocative process using market incentives.

a. Negative Externalities

The costs of using any resource be it land, air, water, or spectrum may not necessarily equate to the costs incurred by the firm utilizing that resource. This is especially true where use of that resource is considered a "free good," i.e., at no cost to the user. For example, by using the river as a source of cooling water, a power plant raises the water temperature a few degrees. Downstream the fishing industry notices a decline in the catch size because the fish no longer breed as well as they did in colder water. The power plant's cost for water amounts to the cost of equipment necessary to handle the volume of water needed, but by using the water they have caused a cost to be incurred by the fishermen. Then the true social cost is equal to the cost of equipment plus the losses suffered by the fishermen. The effect on the fishing industry is the negative externality of this production process. If through environmental laws liability is placed on the power plant, they can choose to pay the fishermen the difference in revenues or to install additional equipment to cool the water back to its original temperature, whichever is cheaper. Assuming zero transaction costs, the power utility now pays

the true social cost of employing river water as a cooling source.

The externalities of spectrum use are not easily characterized and are an impediment to the definition and enforcement of property rights in a spectrum market. There are essentially three major externalities of transmission [32, p. 91]. Each is derived from the unpredictable path and interaction of radio signals. First is the problem of propagation uncertainty. Nighttime sky waves in the AM band are a common example. While we may like to listen to a Chicago station in New York, the New York station is not impressed by the vagaries of electromagnetic propagation which permits a distant station, such as the Chicago one in this case, from interfering with and, indeed, obliterating their own signal. The second source of externalities results from the impossibility of confining a propagated wave to a precise spatial volume or to cause the emitted energy to cease propagating once past the intended receiver. While antenna design can improve the directivity, nothing in current technology can restrict the transmitted signal once it departs the antenna. The end result is that energy from adjacent channels may spill over causing interference. Also, unless the transmitted frequency is of exceptionally superior quality, harmonics transmitted, following the same physical laws as the intended signal, can be an additional source of interference. The third externality is the problem of intermodulation. As explained by Levin:

"(The third externality arises) where several different services operate simultaneously on different frequencies but in the same limited physical area (mountain tops, urban building roofs, naval vessels, etc.). Neither transmitter B or C alone would harm A, but in C's presence B does harm A, through no fault of his own, while C harms neither. A further complication follows from the fact that interference by B of A's reception in C's presence may be due more to the low quality of A's receiver than to the power of B's transmitter" [32, p. 92].

A more thorough discussion of these problems from an engineering point of view is contained in supplement 6 of JTAC's Spectrum Engineering--the Key to Progress [27].

The implications of these three externalities raise serious questions as to the viability of a market which requires for its continued operation a precise definition of the good for sale.

3. Transaction Costs

By doing business in the market place, transaction costs are incurred. They may vary greatly from one market to another; i.e., the transaction costs are a function of the commodity purchased. In each transaction, costs are incurred and it would be too simplistic to assume that a spectrum market, given the definitional problem of property rights could be expected to have minimal transaction costs. These costs are appropriately defined:

"In order to carry out a market transaction, it is necessary to discover who it is that one wishes to deal with, to inform people that one wishes to deal and on what terms, to conduct negotiations leading up to a bargain, to draw up the contract, to undertake the inspection needed to make sure that the terms of the contract are being observed...." [8, p. 14].

In a spectrum market, transaction costs can result from the inability to adequately internalize all the externalities produced by electromagnetic radiation. If the true costs are not assumed by the individual causing or contributing to the interference, then unnecessary transaction costs are incurred in seeking relief from the effects of these externalities [15, p. 13]. If one-to-one negotiations are practical, these costs are minimal. A payment can be made in value equal to the damages incurred and the process is ended. For example, consider the case of where A's television reception is degraded by the transmissions from B's amateur radio station on the next block. A looks outside sees the antenna and assumes B the culprit. A describes the problem he is experiencing to B, arguing that he is sure that B's license requires control of the harmonic emissions which are causing the interference. B agrees and purchases the necessary equipment to modify his station to eliminate the harmful harmonics. The costs to A involve determining the source and the value of his time in negotiating the settlement. In B's case, the costs he incurs are those of internalizing the negative externality of interference. Here transaction costs are minimal. What if not only A but the entire neighborhood were affected by B's transmissions from a relocated antenna. Not only would additional effort be consumed in locating the source of the problem but B, once discovered, might have to negotiate with A through Z. A serious problem may ensue as B attempts to placate all

the TV viewers. It may that the combined efforts to reach a settlement are not desirable. Hence, when the interaction of the property right holders involved affects a large number of other individuals or in turn they are affected, then it may be considered inefficient or inappropriate to enter into private negotiations [8, p. 17].

Further, in the light of positive transaction costs, it is necessary to determine if the regulatory mechanism of the government can deal with the interference problem at less cost than a market mechanism. With no recourse to a more efficient government system, it may be more efficient to ignore the costs of externalities. Simply, if the social costs of externalities exceed the transaction costs necessary to determine liability, then efficiency dictates that transaction costs be incurred [8, p. 18].

4. Enforcement Costs

The costs of policing the interference problem are not currently known. Some attempts, however, have been made to observe actual field conditions for compliance with technical specifications. The FCC's program, the Mobile Microwave Monitoring Program attempts to accomplish just that [38, p. 236]. A market system would not provide such a service. However, it is conceivable that such a service could be offered by a private concern. If the source of interference were unknown, then the individual would be willing to pay the difference between the valuation of his disrupted communications and the costs of the service,

provided he had some reasonable assurance that the interference problem would be rectified.

The creation of a spectrum market has numerous proponents and not a few detractors. While control of interference may be beyond the capabilities of both government or a market, there is a certain appeal in allowing market forces to set a valuation on the spectrum in proportion to demand.

The price established must not be so artificially high that use of the spectrum is foregone for more costly substitutes, nor must the cost inaccurately reflect the true costs allowing congestion to continue unchecked.

D. SPECTRUM PRICING BASED ON MARGINAL COSTS

Marginal cost pricing equates the consumer's willingness to pay for an additional unit of output with the cost of producing that additional unit [11, p. 2]. A balance is reached between the social costs incurred by increased production and consumer satisfaction derived from the additional unit of output. In allocation decisions it is the cost of an additional unit weighed against the satisfaction derived from it which determines how resource allocations are to be made. Thus, allocation decisions are said to be made at the margin. In the long run, however, departures from marginal cost pricing may be necessitated by additional revenue constraints, or by non-constant returns to scale, but these conditions are not examined here.

The idea of spectrum pricing based on marginal costs is not new [31, p. 132-133]. Indeed, allocation decisions are usually made at the margin for other resources. What is needed is a practical mechanism for evaluating spectrum use at the margin to yield an optimal price.

Of particular interest in spectrum pricing is optimal price determination during periods of peak consumption. It is during this peak period that the problem of interference becomes significant. Peak period users should be required to pay a price higher than that of the off-peak user because, at the margin, the costs of production of that additional peak unit of output are higher.

Developments in the extensive and intensive margins have not matched the technologically increased demand for spectrum [31, p. 22]. In the short run the availability of spectrum can be considered constant. Then the problem as seen from an allocation point of view is to set the price sufficiently high so that the marginal cost of utilizing the spectrum is consistent with the marginal capacity of the resource. The consequence of marginal cost pricing is that peak-period consumers will have to pay a price which reflects the incremental costs of increasing capacity [12] [59] [68] [69]. (For a dissenting opinion, see [48].)

In 1957, Steiner reviewed the basic peak-load problem under the assumptions stated below:

1. Demand for a non-storable quantity varies over a given time period;

2. approximation of constant demand can be made if the time period is made small enough;
3. for each subperiod a different price can be assigned;
4. constant returns to scale characterize the technology of supply with capacity fixed over the time period;
5. Pareto-efficient prices can be distinguished for each subperiod [59].

The last point means that efficient subperiod prices have off-peak prices equal to variable production costs and on-peak prices individually covering variable costs and collectively covering capacity costs.

This may appear patently unfair in that the off-peak user can benefit from the capacity while the preponderance of the costs are absorbed by the on-peak user [11, p. 135]. But, because of the on-peak user's desire for consumption when incremental increases in capacity are the most costly, he should cover these costs which would otherwise not be incurred. In essence, peak-load pricing can be considered as a method for charging a price equal to the actual costs of production.

In this case of spectrum usage, the interest is not so much on production as it is on the effects an additional user has both on himself and on others when he attempts to use the spectrum. The problem caused by externalities requires that the peak-load condition be evaluated in terms

of the additional congestion imposed on other spectrum users by an additional user. Even though congestion models for transportation are not specifically intended for the spectrum interference problem, there are significant similarities which can be investigated.

As a traveler enters a highway, costs of fuel, auto depreciation, etc. are incurred. These are the private costs to the individual. In addition, the traveler incurs the cost of the additional time required to complete his journey because the cumulative effect of all the cars on the road is to slow traffic down [41, p. 47]. The sum of this individual average congestion cost and the individual's average variable operating costs gives an average variable cost. This is what the user is responsive to when he decides on entering the freeway. However, the true social cost is greater than what the traveler perceives because, by his use of the freeway, additional costs have been imposed on others [44, p. 19]. As more travelers attempt to use the freeway, the condition becomes more aggravated. This situation is depicted in Figure 3. It is clear that as additional users enter the freeway, a divergence between the average private costs and the marginal social costs occurs [44, p. 16]. If privately-perceived costs deviate from the marginal social costs, then there exists the potential for a misuse of resources. By imposing a congestion toll equal to the difference between the private costs incurred by the user and the marginal social cost, greater allocation efficiency can be achieved.

Congestion Costs of Spectrum

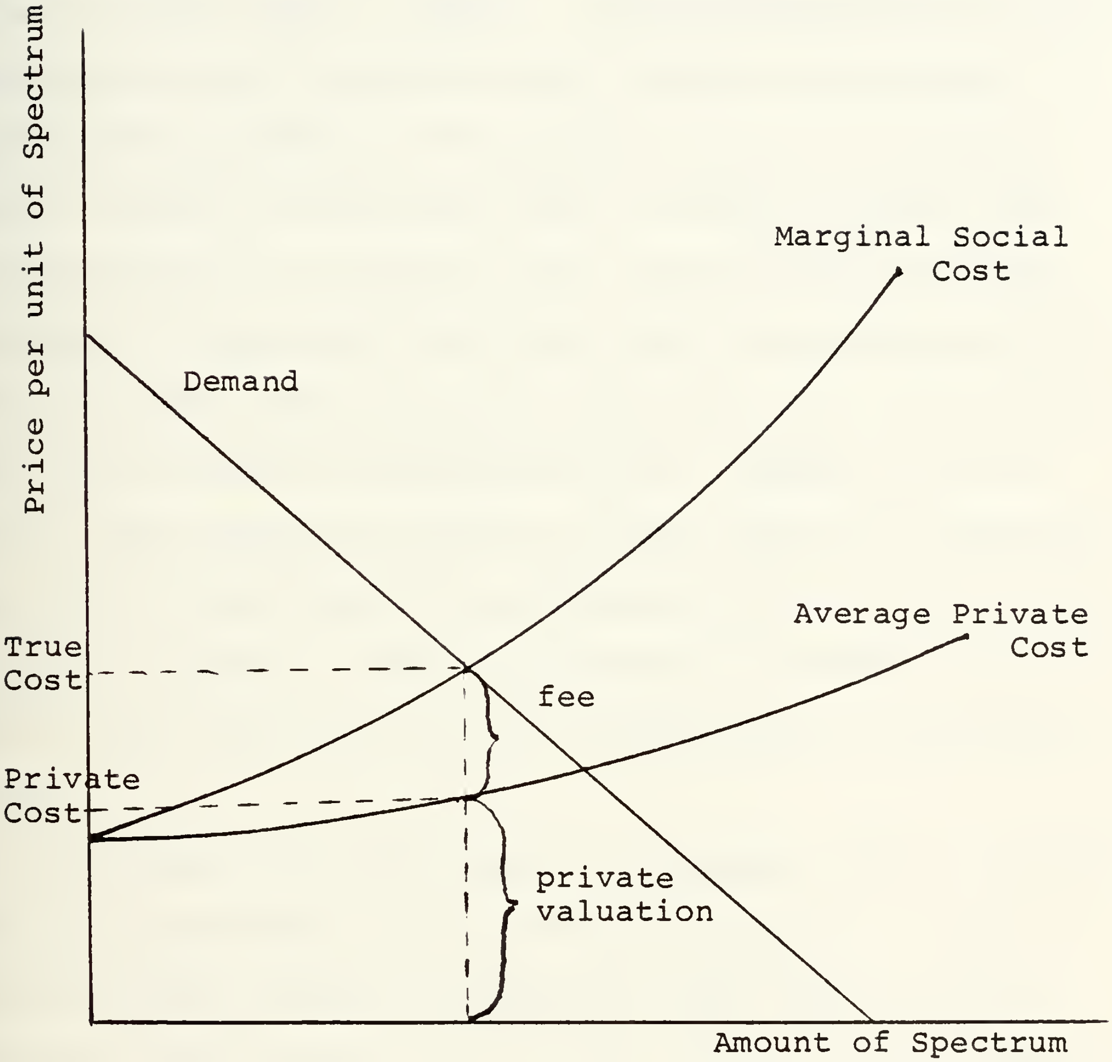

Figure 3
Adapted from [43, p. 19]

The state of spectrum management is analogous to the congestion problem. For a fixed level of technology within an allocation, there is a finite user capacity within any given time and spatial domain. This is the short-run situation. Because the cost of spectrum use involves only the cost of appropriate equipment, i.e., private costs, an inequality exists between private costs and the marginal social cost of spectrum use. The social costs of externalities which increase with each additional user plus the average private costs represent the true cost of spectrum use. The initial user has no need to internalize costs. However, as additional users enter, the ability of the spectrum to accommodate the increased demand may decrease proportional to the congestion present. That is, if demand increases persist, then at some level of congestion unacceptable interference occurs.

If an empirical relationship is assumed, where an average level of interference is defined as a function of total social cost and spectrum use density, then there are two important implications [44, p. 16]. First, as the number of spectrum users increases the additional social costs caused by these users steadily increases. Secondly, for any allocation band there is some technologically dependent capacity which defines the maximum acceptable level of interference.

The marginal social cost can be defined as the cost an additional user incurs plus the costs an additional user imposes on others by increasing the level of interference

or the waiting time imposed by channel saturation. Queuing time in a heavily used single-channel mobile radio is an example of the costs imposed on others. The difference between marginal social costs and average private costs reflects the increased costs an additional user imposes on those currently using that allocation. Put differently, if the user could be induced not to use spectrum or at least not as much, he would reduce the aggregate cost to other users. If he were indifferent, then the costs born by the user and those imposed on current users, evaluated at the margin, would dictate the more efficient choice. That is, if the new user's marginal cost exceeds the aggregate marginal cost of current users, the new user should be required to pay the higher amount.

The marginal cost price derived for use of the spectrum should consist of individual user costs plus a fee as shown in Figure 3. The fee is fixed at an amount equal to uninternalized costs. The difference between the true cost to society and those costs assumed by the user are the uninternalized costs.

Then, for any level of capacity a price could be determined. This price would then indicate the willingness of the individual to accept all social costs involved in spectrum use and would help curtail demand for spectrum by eliminating the indifferent user present because of the current no-cost policy for spectrum usage. A lower fee would promote spectrum usage with associated social costs greater

than the costs incurred by the operator. On the other hand, an excessive fee would discourage potentially efficient users, causing them, in some cases, to invest in artificially attractive spectrum substitutes.

When then is a socially efficient price? As seen in Figure 3, even if the spectrum user correctly values the costs of using spectrum as he perceives them, the amount he would be willing to pay would be less than that calculated from the marginal social cost of spectrum. The perceived price must be adjusted upward in an amount equal to the fee as depicted in Figure 3. This arrangement would yield a socially optimal price.

By adopting an auction technique, a Pareto-optimal valuation can be made of the private costs the user incurs through use of the spectrum. But, since the user is only influenced by the effects interference would have on him, he is not compelled to bid the true social cost of spectrum usage. A fee is required to obtain the correct price. As noted previously, spectrum fees have some fundamental problems. In this instance, though, determining the correct amount is simplified because part of the total cost includes the previously determined private cost. Since the primary concern in spectrum management is to decrease interference, a fee which covers the administrative costs of conducting an auction and handling interference complaints might serve as an appropriate surrogate measure. It is thought that administrative costs for a more elaborate fee determination

mechanism would be excessive. By a combination of auction price and fee, a price solution would be determined which is an approximation to the optimal price in the presence of transactions costs. This is usually referred to as a second best solution [4, p. 265].

If a limited market structure for spectrum is assumed and allocations are described by bandwidth and legally permissible use, then as the capacity constraint imposed on each allocation is reached a corresponding price increase occurs. Between allocations, a difference in maximum willingness to pay for an additional unit of spectrum causes a price increase in one allocation relative to another. Reapportionment of the allocation to a point of price equality is indicated.

If the allocation method were inflexible, then the additional consumer surplus captured by an excessive price in an already congested allocation could be regarded as a tax, if adjacent, substitutable allocations were not at capacity. In such a situation, spectrum allocation would not be efficient. If the capacity, i.e., bandwidth, of the highly demanded allocation were increased at the expense of an allocation experiencing less demand then by reapportioning the allocation, more efficient use can be made of the spectrum.

VI. MARKET PROPOSAL

This market recommendation incorporates three requirements which have been developed:

1. Frequency coordination
2. Responsiveness to technology
3. Spectrum pricing.

Each requirement is amplified below.

This proposal uses input rights and develops a market mechanism which is designed to allow the individual firm to make optimum resource allocation decisions based on what is perceived as the marginal rate of technical substitution between capital investments and spectrum.

A. REQUIREMENTS

1. Frequency Coordination

The first efforts by the government in regulating access to the spectrum were to provide a centralized modus operandi for frequency coordination. Realizing the benefits attainable by common agreement over frequency usage, user acceptance was immediate. The system has evolved, however, into one completely regulated which suffers from an inability to respond to demand. Any market system proposed must also capture the benefits of frequency coordination while removing the constraints imposed by and the economic implications of resource regulation. The positive aspects of spectrum management in terms of coordination must be retained.

2. Responsiveness to Technology

Lower electronic costs have created a demand for spectrum unmatched by technological improvements in the extensive and intensive margins of the spectrum. However, any proposed system must be responsive to the additional spectrum supply created by technological advances. As shown above, the firms' decision rule on resource allocation is dependent on the regulator's choice of spectrum bandwidth available for a particular service. To permit economic efficiency in resource allocation decisions, the user must be allowed an unrestrained choice in the bandwidth requirements of their particular system. Because the regulated system requires a bandwidth based on previous technology, the allocation decisions are suboptimal. A market system which provides the opportunity to obtain an efficient amount of spectrum decreases the opportunity cost of available but unused technology.

3. Spectrum Pricing

Spectrum pollution or congestion is a function of both the increased demand for spectrum caused by lower cost electronics and the supply of spectrum available. Since for any sufficiently small period the spectrum supply is constrained by the technology available, the resulting situation can be described as a peak-loading problem. By applying both peak-load pricing theory and congestion theory of transportation economics to the spectrum allocation and assignment problem, a marginal social cost is derived to

provide a basis for efficient spectrum price. The marginal price produced includes the costs of congestion imposed on others by the additional user. The marginal pricing method provides a mechanism for valuation of an additional unit of spectrum to the firm. By adopting a marginal pricing method, a more accurate valuation of the social cost of fully internalized spectrum is achieved.

B. ELEMENTS OF THE MARKET MODEL

This model attempts to incorporate the requirements above into a viable allocative mechanism using market incentives as the dyamnic force. It is not designed to provide the absolute answer to all the problems of spectrum allocation but focuses on only one of the many potential markets in spectrum allocation. It is intended for use primarily in the Land Mobile Radio Service (LMS). LMS offers an excellent opportunity to apply economic techniques for the following reasons:

"1. Many land mobile channels are congested in many parts of the country, while some channels are under-utilized in those same areas;

2. Several technological methods are available for increasing the efficiency of spectrum utilization, but are not being employed, or are only being partially employed;

3. The FCC has received proposals to allocate additional frequencies for the LMS, some of which it has acceded to, without finding a way to induce users to employ known methods of increasing the utilization of the spectrum;

4. Continued growth of the LMS will increase loading and congestion (recent growth has been on the order of 12 percent per year, with 100,000 applications filed each year)" [1, p. IX-1].

The band assignment method of Dunn and Owens allows the owner to assign portions of the band to other users as a form of secondary rights [21]. For example, if a new type of mobile radio system were to become available that would permit high quality service to be obtained from 1/5 of the presently used band, 3/5 of the band might be sold to another user group for enough to pay for converting to the new spectrum-efficient system and 1/5 might be retained to allow for future growth [1, p. IX-39] [20].

The market model proposed in this thesis articulates a mechanism for efficient handling of these bandwidth portions. Indeed, by explicitly defining these portions of bandwidth, spectrum pricing techniques can be incorporated.

The model provides for complete freedom of choice of the technology utilized, but requires the user to maintain strict adherence to the specifications of input parameters which are necessary conditions for issuing the license. This model provides the incentive for optimizing spectrum use both by use of improved technology and by imposing a congestion toll on additional users. By pricing spectrum use at the margin, the cost incurred by society for an additional user is more fully internalized.

There are six basic features to the model.

1. allocation determination
2. assignment bandwidth
3. price determination
4. titles and license procedure
5. license transferability
6. market timing.

Each element provides an integral part of the market mechanism designed to be responsive to the system requirements detailed.

1. Allocation Determination

Given the varying elasticities of substitution among different portions of the spectrum, the difficulty in defining acceptable property rights and the potential loss of frequency coordinated benefits, a suboptimal allocation of spectrum must be made initially. This allocation will be designated for a particular use only to avoid electromagnetic compatibility problems associated with adjoining or intermingled disparate services. The frequency range of each allocation is controlled by the differences in marginal products of bandwidth and price between adjacent allocations [54, p. 14] [25, p. 153]. That is, if the peak-load price of one allocation exceeds that of the next, then efficiency dictates transfer of spectrum to the first allocation in the amount necessary to produce equal marginal products in both allocations. An evaluation period equal to that of an individual license period would be used to calculate an average marginal product for each allocation. If transfer of spectrum was necessary, it would occur on license expiration of the assignments involved by allowing the FCC to buy the needed bandwidth at the bid price. This allocation method can provide a dynamic mechanism for increasing supply in a highly demanded service without resorting to intensive or extensive expansion of available supply and the concomitant research and development costs.

2. Subassignment Bandwidth

In lieu of administratively defining the bandwidth of an assignment equal to a regulator's assessment of current technology, a small unit of spectrum, the subassignment, is offered. In some respects, the subassignment is much like Jackson's Space Segments (SS's) [25, p. 76]. The dimensions in bandwidth are material only in that they represent a unit of bandwidth which cannot support the desired service with a reasonably foreseeable technology. Although administratively defined, there is no need for precision in the information needed for an adequate decision.

This subassignment is sufficiently small to accommodate two market requirements. First, by providing smaller units of spectrum the individual firm retains the capability of determining its optimum allocation scheme. Implicit in this feature is the system's ability to incorporate new technology without penalizing the firm for making that choice as is now the case where spectrum is a free good.

New technology can provide identical system effectiveness without utilizing the 25 KHz bandwidth and narrow band FM modulation now required by the FCC. Recent technological developments, although not entirely tested, indicate that from seven to ten times as many voice channels could be obtained from the VHF and UHF allocations for land mobile radio [36, p. 34]. This feature provides incentive to invest in more spectrum efficient equipment, thereby

stimulating technological development in both the extensive and intensive margins of spectrum.

Secondly, the use of subassignments permits the firm to place an individual valuation on an additional unit of spectrum at an approximation to the margin. By decreasing the bandwidth of the subdivision, the marginal price per unit of spectrum is reached in the limit. For reasons of practicality, an approximation of the limit is required.

Pricing spectrum at the margin permits efficient resource allocation. However, market proposals to date have used essentially an average value for spectrum in determining price to the firm. While this price may be a marginal one to the market, it is not a marginal price to the individual firm. Hence, this proposal permits the firm to respond to changes in technology and market demand in an individualized and more efficient manner.

By providing spectrum subassignments in the market, the firm can, for any available technology, evaluate the substitutability of production inputs at the margin to obtain resource allocation efficiency.

3. Price Determination

Price determination consists of two separate parts: an auction price and a regulatory fee. The auction technique for a spectrum market is chosen because of the rapidity with which the new owner is chosen and the minimal transaction costs involved. The English auction, where the highest bidder pays the second highest price is favored for

several reasons. First, the mutual best response bidding strategy is relatively simple: it is optimal for the bidder to bid the true value for the subassignment auctioned. Also, the probability of winning is independent of the profits realized when the winner pays the second highest bid [1, p. VIII-21]. Secondly, Vickery has shown that in general the English auction leads to Pareto-optimal results [61]. This is especially important in this model because it reduces the possibility of a self-imposed tax by over-bidding to obtain the n^{th} subassignment for the technology chosen. Third, the English auction produces a higher variance of the winning bid which is not preferred by a risk averse seller [1, p. VIII-21]. Since the FCC is to act in the "public interest," this factor is not significant. However, to insure propriety in payment, all bids must be made public.

The second portion of the spectrum price is an administrative fee which is assessed to cover the cost of the auction system and the costs of enforcement. As seen in Chapter V, in the face of externalities, average private costs do not equal marginal social costs. To obtain a socially efficient price a fee equal to the difference between average private costs and the marginal social cost must be included. In the interests of minimizing the expense of determining an optimum fee, a surrogate measure of administrative costs is employed in this model.

4. Titles and License

A successful bid provides the individual title to that subassignment. Presentation of titles in the required amount of bandwidth for the particular transmission system chosen is sufficient to award station license. The current system for determining power output, antenna height, would still be maintained because of the experience in this method, and input specification for line-of-sight propagation provides a close approximation of the radiation density and potential useful range of the equipment operated.

A centralized market is used for minimization of transaction costs. It provides a forum for information exchange and a means of obtaining up-to-date information on current title holders. In essence, it would allow the FCC or a duly authorized body to conduct the auction, act as a spectrum broker and record license and title registration. Because of the nature of line-of-sight transmission, a number of regional offices and markets would permit a more individualized response to the demand for spectrum in two ways. It would allow reallocation of spectrum by geographic region not nationwide as now done. It would provide a geographic insulation between regions that may have considerably different demand characteristics for a service. Hence, the price paid reflects regional demand. Secondly, it would allow a faster response time in issuing and recording the license.

5. Transferability

The sale of a subassignment title to another is not prohibited. The only restriction placed on transfer of a title is that the new owner be required to register with the regional office. This provides an opportunity to update the listing of current title holders and it serves to protect the buyer by allowing a title search to be performed [54, p. 17]. This would prevent sale of illegally or fradulently acquired titles to an unsuspecting buyer.

If the title holder desires, he may offer some or all of his titles at a regularly scheduled FCC sponsored auction rather than placing them for sale himself. This flexibility permits minimization of transaction costs by providing a centralized mechanism for title transfer. The potential buyer need only contact the regional office to obtain a complete listing of cleared titles which will be auctioned. Also available would be the current prices for recent subassignment sales. Thus, the potential buyer would be able to obtain information, specific for his geographic area, that would be necessary for the firm to make an optimal resource allocation decision.

6. Market Timing

This feature may be the single most important element to a successful spectrum market. There are actually two time periods involved and each can have a major impact on optimal spectrum pricing. The first is the frequency of government sponsored auctions and second, the length of time prior to mandatory title reauctioning.

The length of time between auctions is important to alleviate unnecessary transaction costs by too lengthy a period in which spectrum may be used inefficiently. Also, if the auctions are too frequent, there would be a tendency to offer bids which are not true valuations to the user but are essentially those of the previous auction.

Mandatory reauctioning of the license would occur at an interval sufficiently long to permit full depreciation of the licensed equipment. The period would commence on issuance of the title. If the current title holder wished to retain a title he now held, participation in the auction would be required. If the firms' bid were unsuccessful, then title would pass to the successful bidder at the second highest price bid with payment made to the previous title holder. The rationale for mandatory reauctioning is that it forces the firm to reevaluate its resource allocation decisions in the light of current market competition. It requires the firm which is inefficiently using spectrum to bear the financial burden of its inefficiency if continued operation is desired.

In addition, the competition would stimulate technology. If the firm decides that the titles now held would be too expensive under current market conditions to successfully bid on all of them, then a decision could be made to make a determined bid for only a fraction of the titles now held and finance newer equipment requiring fewer titles from the proceeds of the uncontested titles. This option

would prevent the firm from placing exorbitantly high bids to re-obtain the current held titles. Such behavior would result if the current equipment is over-valued. While the sunk cost of the equipment should be of no economic concern when faced with a resource allocation decision, there would be a tendency to overstate the value of existing assets at the expense of socially inefficient spectrum usage.

If the title duration is set too short, then the bid would be high to protect the capital investment that the equipment represents. The difference between the true valuation and the successful bid price, if the latter were higher, would represent a tax on undepreciated capital assets which is neither intended or desired. If the period were too long, then the firm would avoid evaluating spectrum at its true social value and would provide no realized incentive to acquire newer spectrum-saving technology.

C. EVALUATION

A key point of contention may be that the bidding strategy adopted for the final necessary subassignment is suboptimal. To insure winning, the bid may be made artificially high. However, if successful, only the second highest bid price need be paid which offers some protection from self-taxation. If another firm has the same idea, the actual selling price may be considerably higher. While it could be argued that an inefficient price has been set, it is also reasonable to indicate that this higher price is, indeed, a truer indication of spectrum valuation at the

margin to the individual user. A more detailed analysis would be required to determine the optimal bidding strategy given the requirement to complete a set of titles.

There are no considerations given to a user which require a last subassignment. If their bid is unsuccessful, they can resell the titles or obtain more spectrum-efficient equipment. If a competitive price is to be established, there can be no guarantee of bidding success. Freedom to fail is an essential ingredient in competition. As congestion increases, it winnows out the marginal user.

Another possible result of this model may be the creation of a future market in subassignment titles. Speculation against future prices may provide greater stability in prices. Also, it would provide options for potential buyers to purchase subassignments. Since there is no requirement that a subassignment title be used to obtain a license, it could be traded like any other commodity. If the investor's present value of future sales were greater than current market prices, it would be more efficient for the investor to hold the title for future sale.

No consideration is given in this model as to the legality of this proposal. Indeed, there is considerable conflict over who currently owns the spectrum, and whether the government can assume ownership with intent to sell rights to spectrum use. Also, under current law the FCC may not be empowered to collect the proceeds of the initial auction. These issues should not constrain the proposal.

If they, in fact, can provide a greater allocative efficiency, then the law should be altered to accommodate the accepted proposals.

VII. CONCLUSION

This thesis reviews the nature of electromagnetic propagation and the development of governmental regulation which seeks to control the interference resulting from unrestricted use of the spectrum. Also described are proposals for the introduction of economic incentives into the spectrum allocation mechanism. These are of two distinct types. The first group provides for a free market where spectrum allocation is accomplished in a competitive market by defining a system of property rights which allows the spectrum to be traded as if it were any other commodity. The second group proposes a limited market structure which defines the rights of the user in terms of technical input specifications. Additionally, the second group confines its economic proposals to individual services, recognizing the relative inelastic substitutability among different frequency ranges of the spectrum.

Next, the production function of the firm is investigated to ascertain the effects of a positive spectrum price on the choice of telecommunication input quantities. The central argument is that the firm in seeking to make an optimal choice must evaluate costs at the margin. By pricing spectrum at the margin, not only will the firm be able to approach economic efficiency but such marginal valuation can serve as an explicit indicator of the relative valuation of spectrum in different spectrum markets. Thus, allocations can be adjusted to more appropriately reflect spectrum demand.

Derived from the preceding discussions, this thesis proposes a limited market for the land mobile radio service. Its main features are decentralized control, subassignments, pricing method, and title transferability. This market recognizes that demand elasticities for spectrum vary with geographic area and that a responsive market must recognize this fact. Therefore, while the controlling agency may serve as the focal point for the spectrum market, the sphere of influence is restricted to a specific portion of the country. This would permit a more flexible allocation scheme than currently available and would free regional users from the restrictions of nationwide allocation procedures.

The subassignment permits the technical and operational freedom necessary for optimizing the use of spectrum. This feature allows the user to determine spectrum bandwidth requirements in trade-off with equipment requirements. The user would no longer be constrained by the fixed amount of spectrum it considered necessary for continued telecommunication operation. Indeed, if demand continues to escalate, a mechanism is provided to allow the use of more technically advanced equipment, without penalizing the user as is now the case.

The pricing method is comprised of two portions. The first part uses the English auction technique to determine the true value of the subassignment to the bidder. Since the successful bid represents only a portion of the marginal

social costs, a fee is imposed using administrative and enforcement costs as a surrogate measure.

The feature of transferability allows the user to divest portions of his acquired spectrum under market valuation conditions. That is, if the title holder could realize an economic gain by sale of portion of his titles, then he is free to do so. The only restriction on transferability is the requirement to reauction all titles after they have been held for a prescribed length of time. In this manner, title holders would be continually required to assess their current spectrum needs in the light of current market conditions.

As technology continues to offer greater capabilities at cheaper prices, the demand for spectrum can only be expected to escalate. The demands on administrative spectrum assignment will only get worse. By adopting economic incentives to conserve spectrum usage and by removing legislative restrictions which impede efficient use of the spectrum, the economic potential of the spectrum can be more fully explored. This thesis provides a feasible, albeit limited, mechanism for improved management of this important natural resource.

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